Optical Backplane and Clock Signal Distribution Systems

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Outline

(1) Introduction to backplane and clock signal distribution systems

(2) Limitations of electrical interconnection

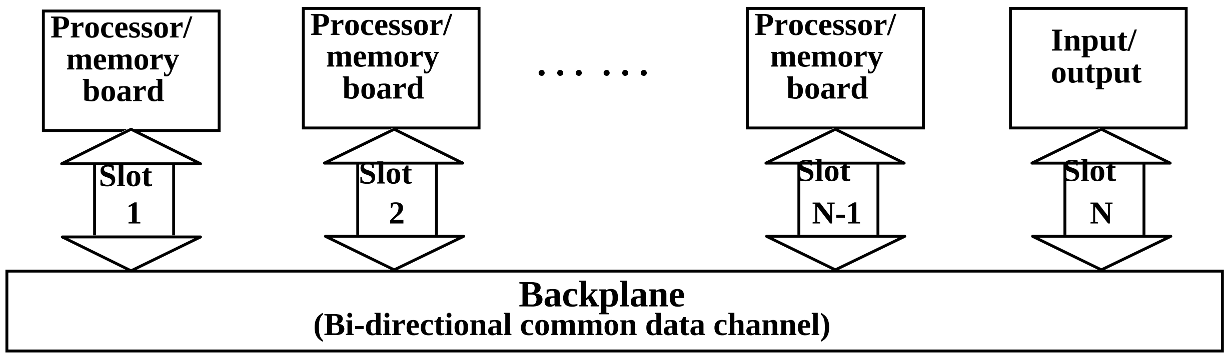
(3) Optical realization of backplane and clock signal distribution systems

(4) System characterization

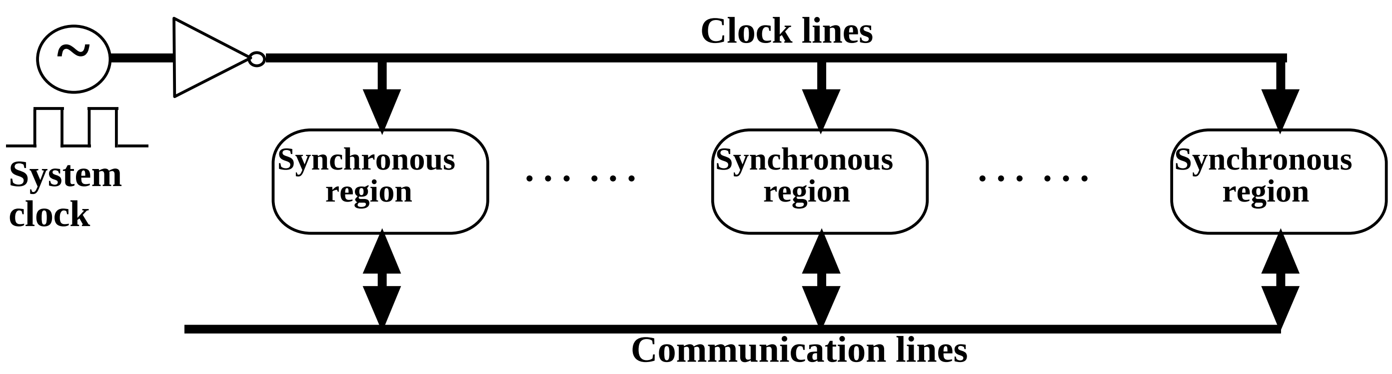
(5) Proposed future works

Definitions of backplane and clock distribution systems

Bi-directional backplane system:



Clock signal distribution system:



What's wrong with electrical interconnection?

Increase in computing power

<=> shrink in clock cycle time and pulse widths

=> increase in bandwidth to keep signal integrity

Limitations of electrical interconnection:

capacitive loading
crosstalk
reflection
switching noise
skew
power dissipation

=> Bandwidth of electrical backplane is limited

Limitations of electrical interconnection

Examples

Processor speed as high as 500 MHz

But board-to-board data rate ~ 100 Mb/s

VMEbus and Futurebus data rate < 100 Mb/s

PCI bus: maximum clock rate 66 MHz

=> Optical interconnection necessary

in high speed (> 200 MHz), long distance (> 1 cm) communications

Advantages of optical interconnection

Transmission media (waveguide or free-space)

more bandwidth without

transmission line effects
capacitive loading
complicated termination

High speed optoelectronic devices

transmitter : fast modulation with small current

receiver : high sensitivity with large dynamic range

Optical interconnection in VLSI systems
Various schemes

Fiber optics:

flexibility in geometry of detector positions
suitable for long distance communication
(e.g., machine-to-machine)

bulky; point-to-point connection

Waveguide optics:

suitable for chip-to-chip interconnection

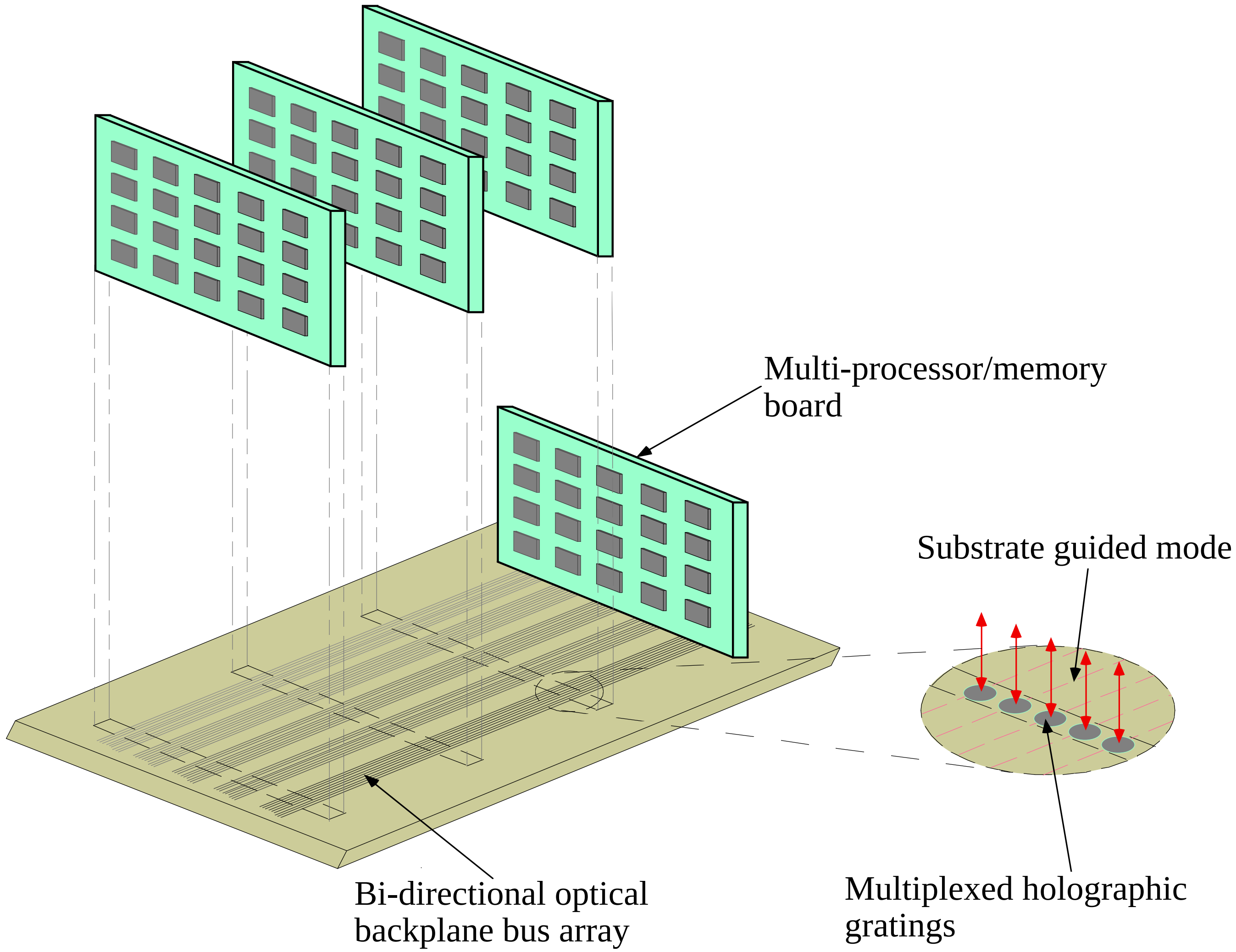
45° waveguide mirror not compatible with
VLSI technology

Free-space optics:

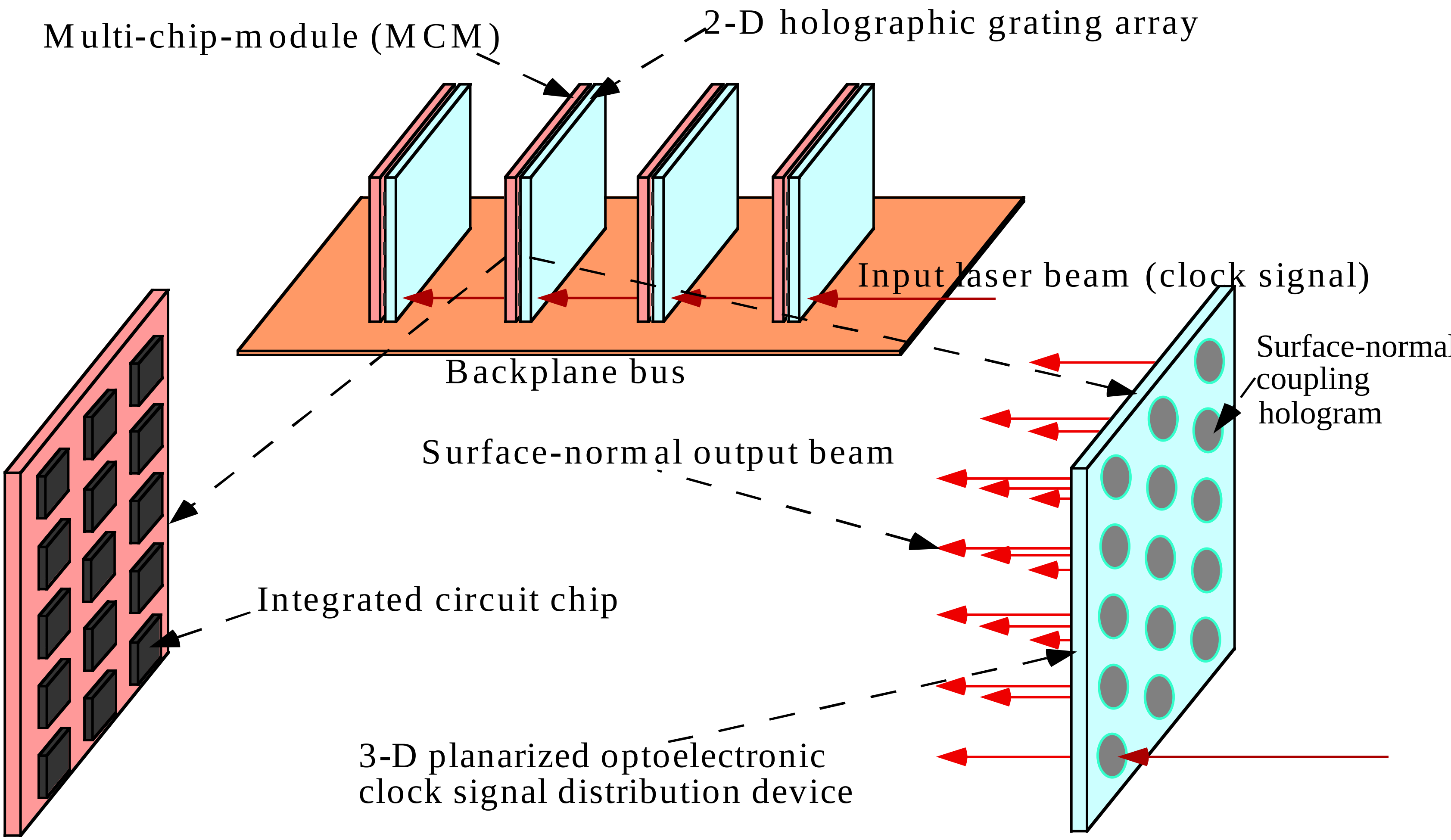
massive fan-out; large degree of freedom;
lower propagation delay

control of beam steering

Optical realization of bi-directional backplane system

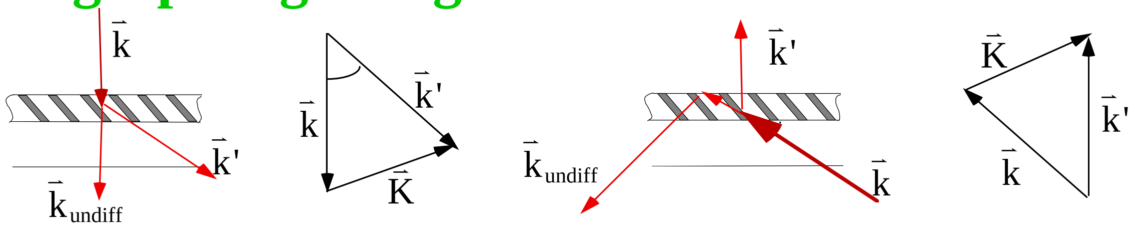


Optical realization of clock signal distribution system



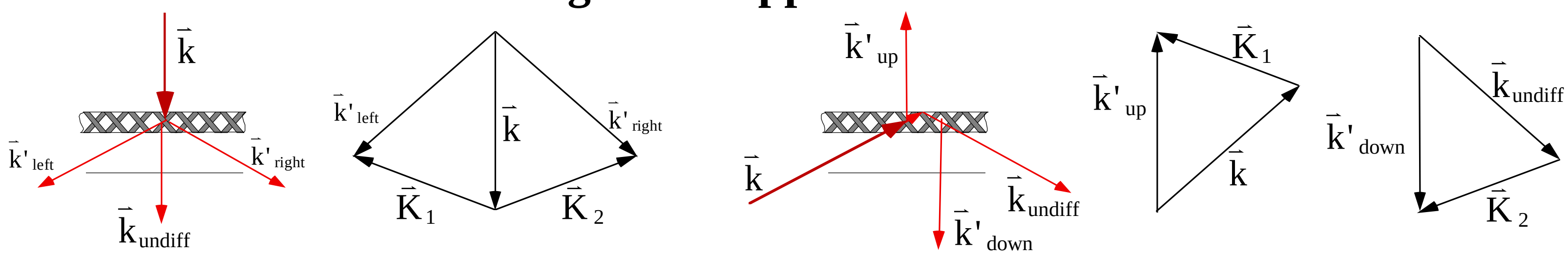
Design of holographic grating elements

Single holographic gratings:

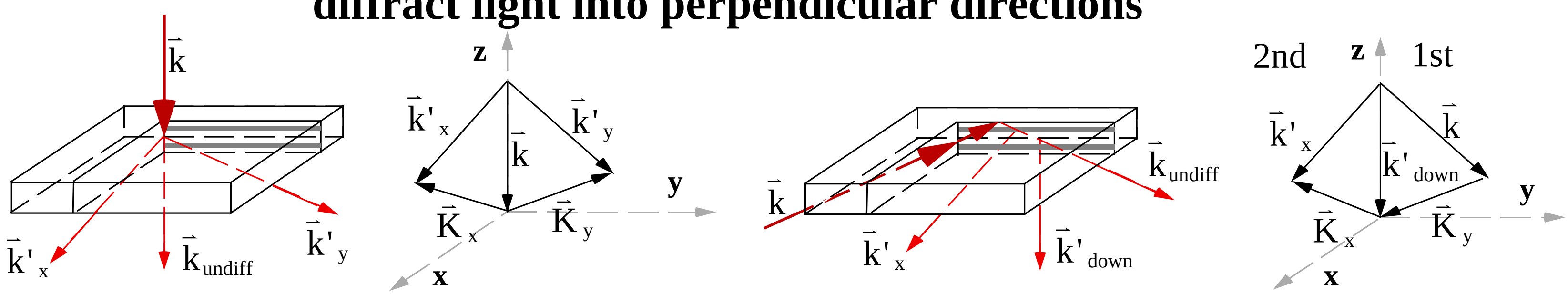


Multiplexed holographic gratings:

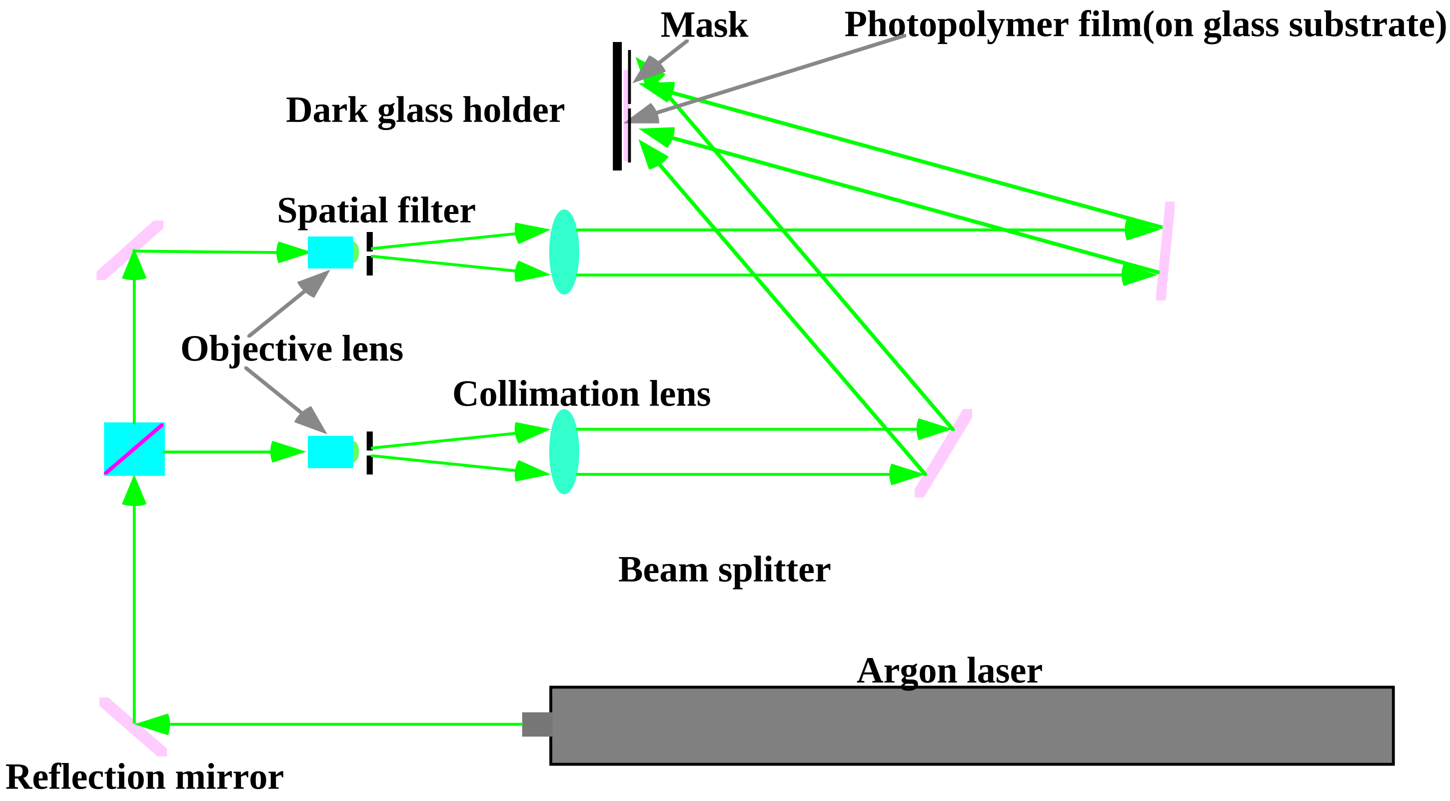
diffract light into opposite directions



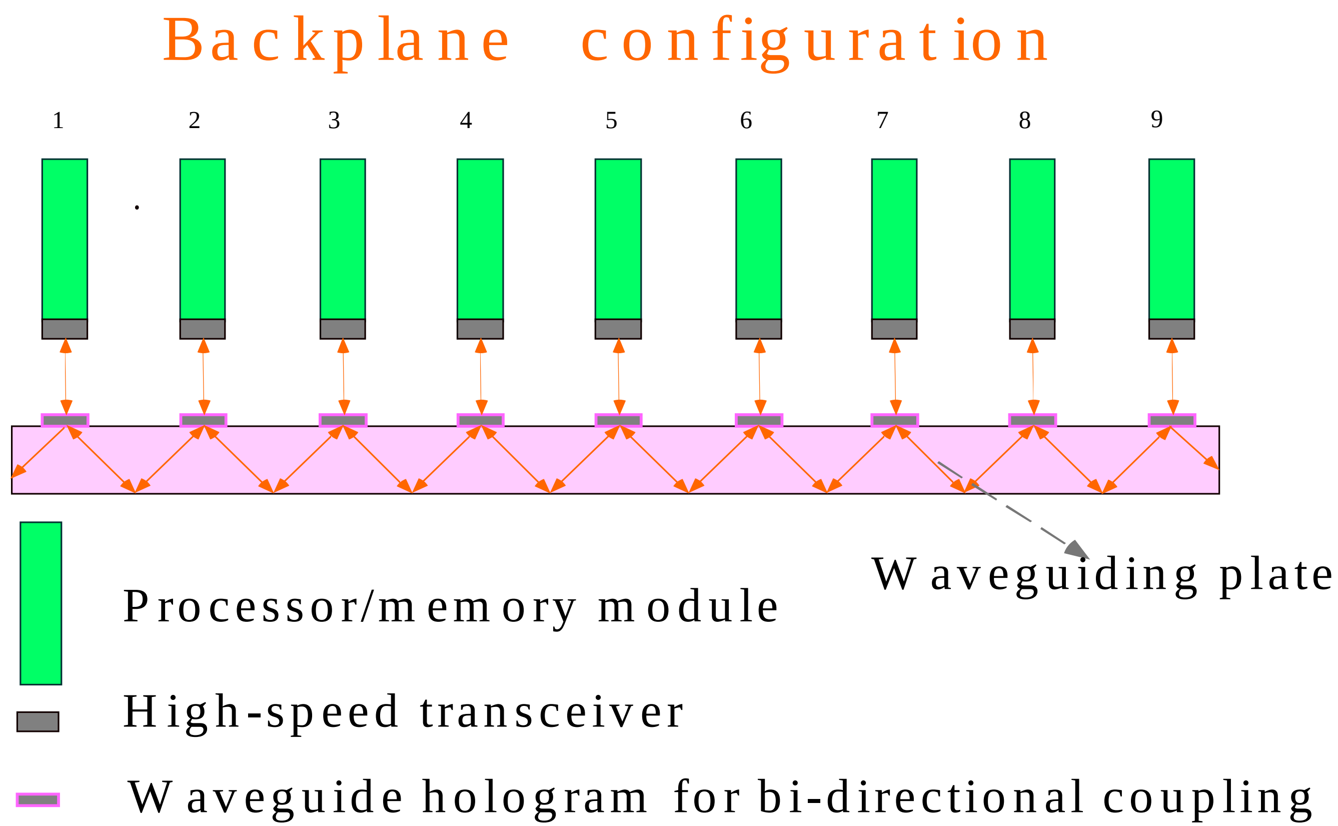
diffract light into perpendicular directions



Fabrication of holographic grating elements

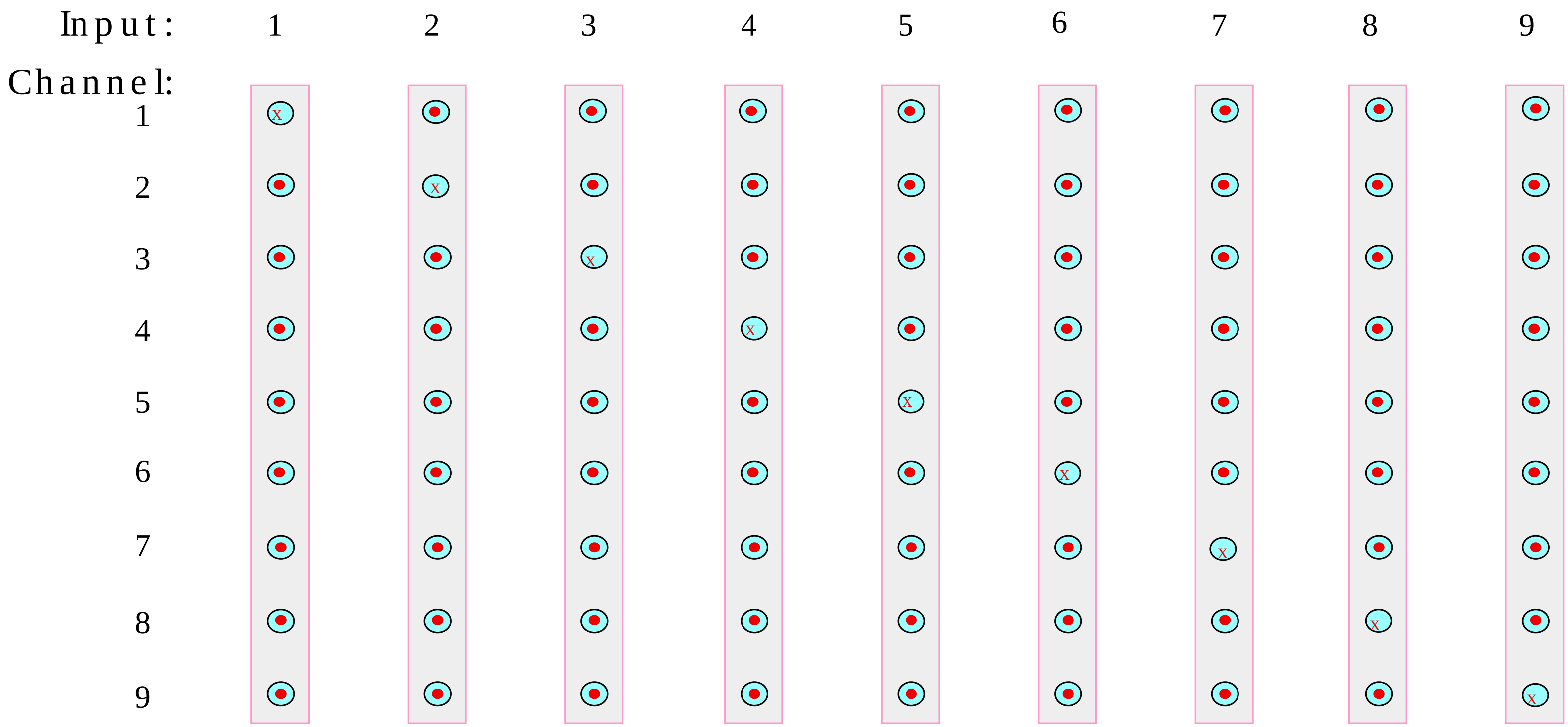


Bi-directional optical backplane bus with single bus line



Bi-directional optical backplane with a single bus line

Channel communication



Bi-directional optical backplane bus with single bus line

Experiment demonstration

Channel: 1 2 3 4 5 6 7 8 9

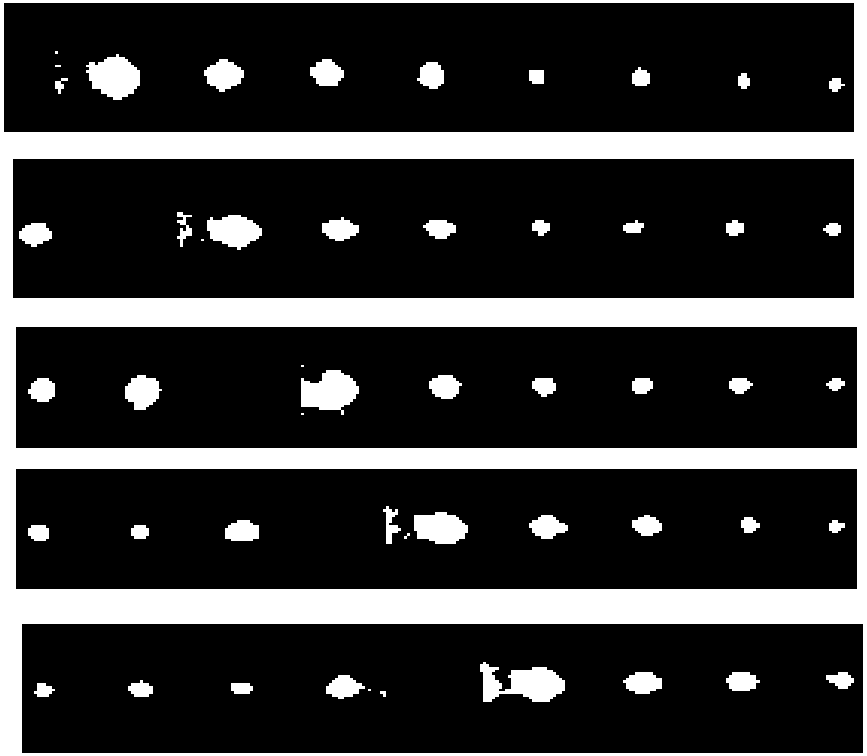
Input: 1

2

3

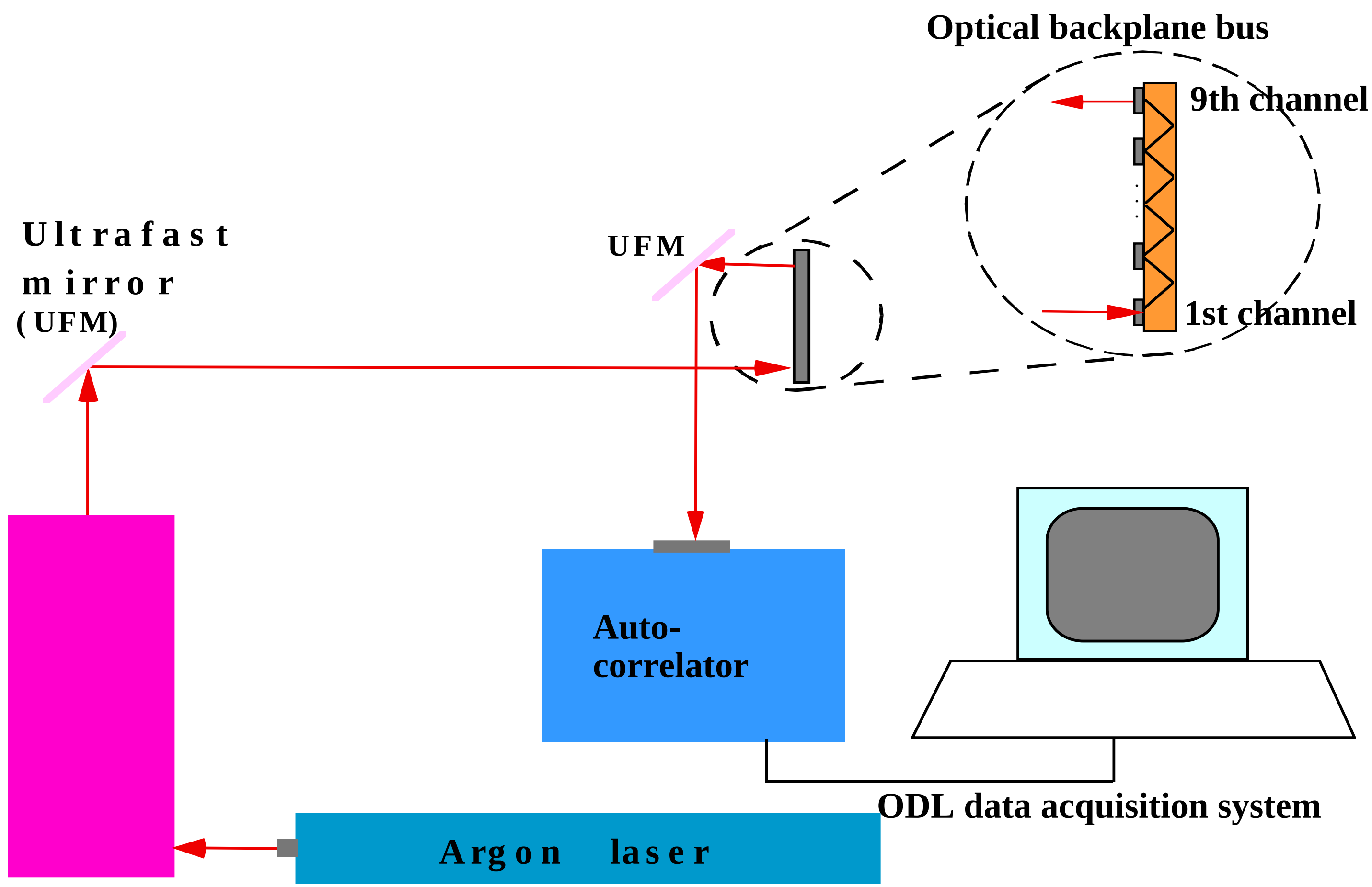
4

5

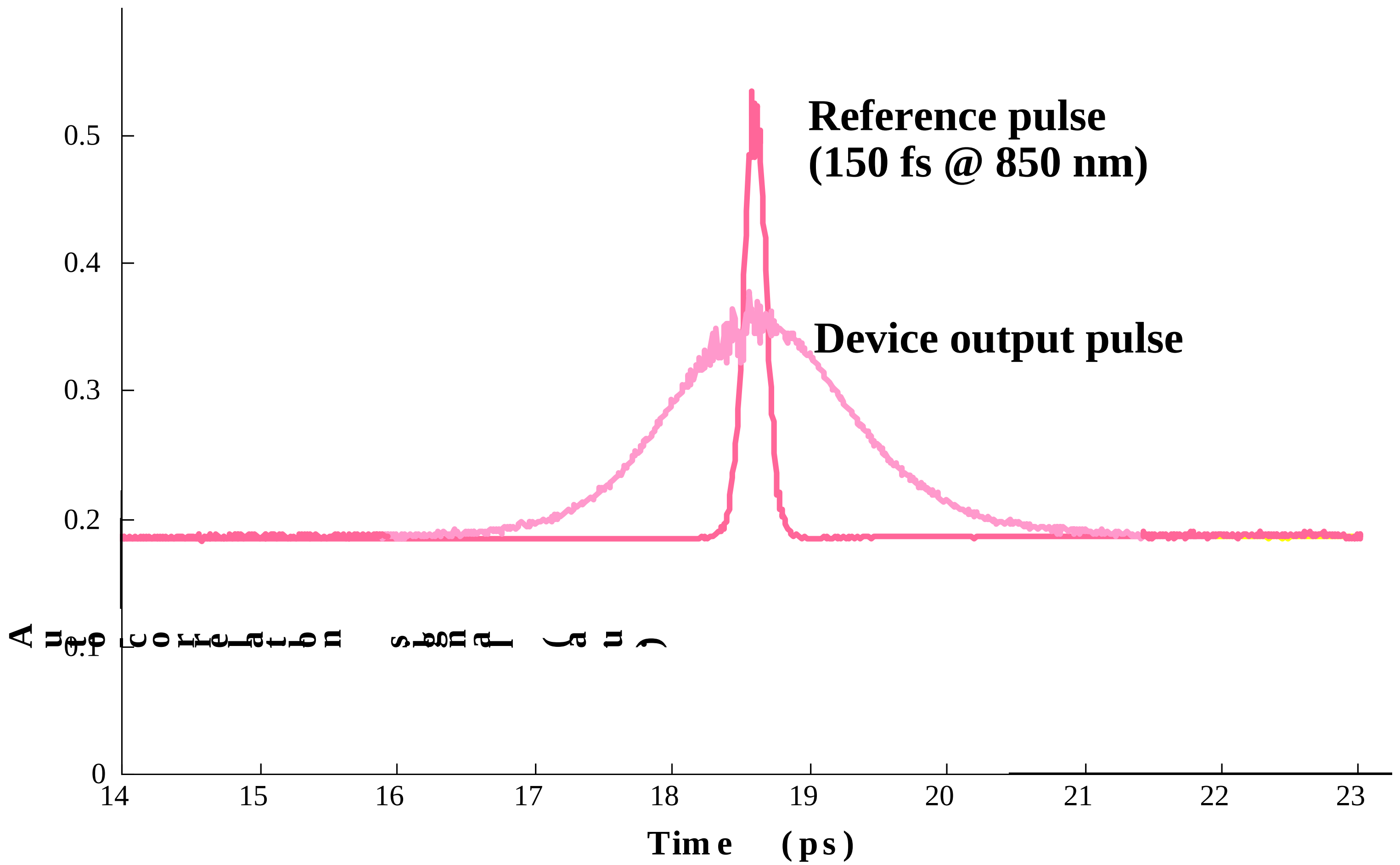


Bi-directional optical backplane

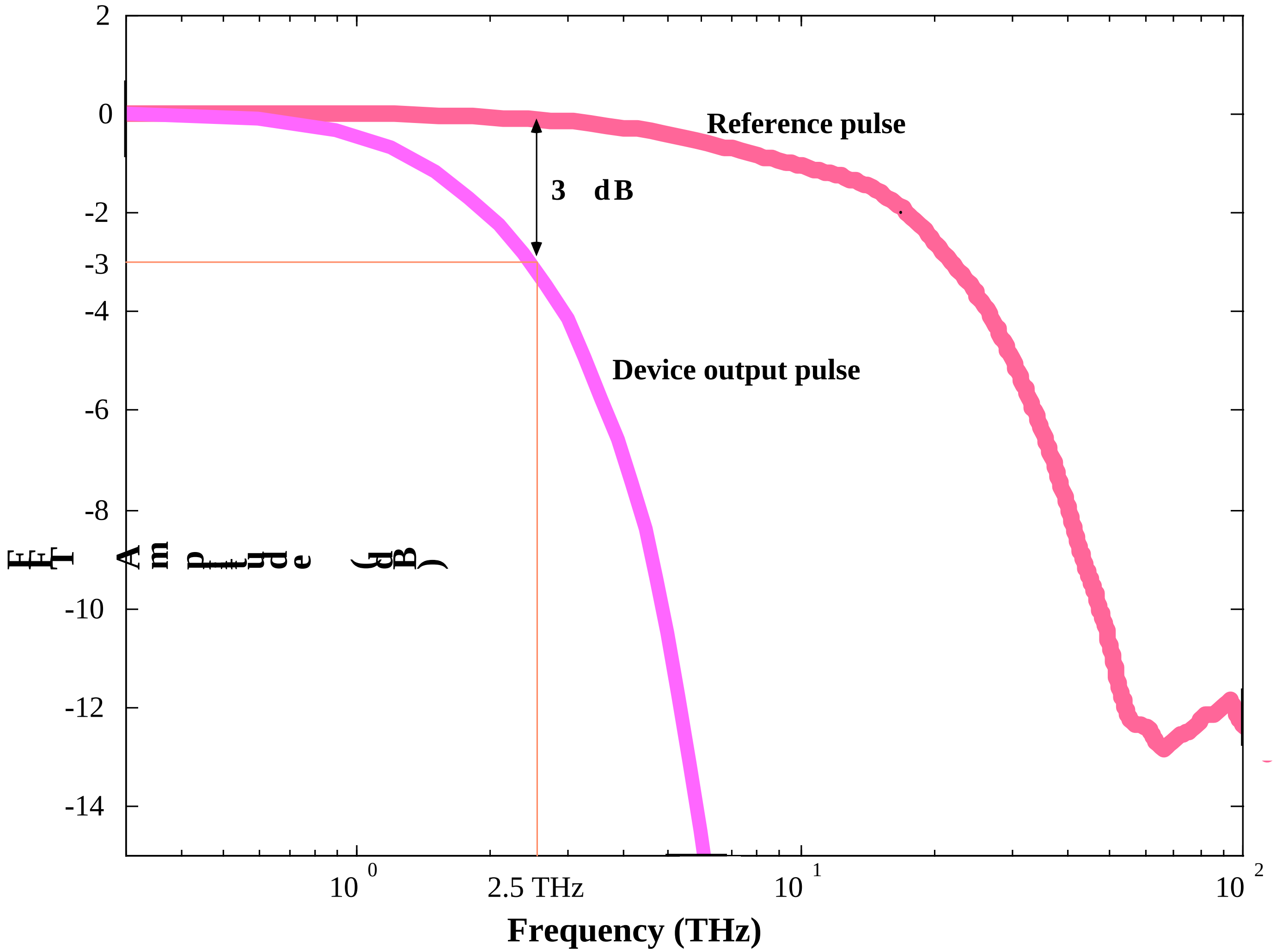
Bandwidth measurement setup



Pulse broadening by the optical backplane



Frequency response of the optical backplane

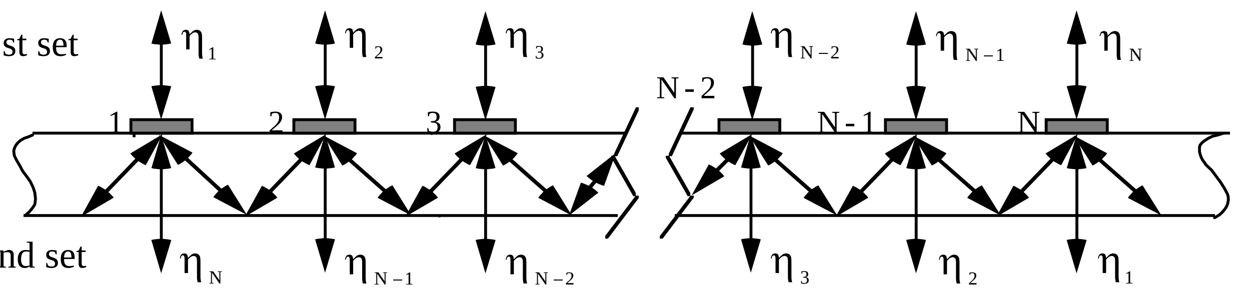


Fan-out intensity optimization of the optical backplane

Goal : to minimize output intensity fluctuation

Output power: P_{ij}

Diffraction efficiencies: 1st set



2nd set

P'_{ij}

Fan-out intensity optimization

Assumptions :

(1) Neglect reflections and absorptions

(2) To prevent power leakage, $\eta_1 = 1$ and $\eta_N = 0$

Transmission function :

energy of substrate guided beam transmitted
from one output channel to the next

Fan-out intensity optimization process

(1) Express fan-out intensities as functions of diffraction efficiencies $\eta_i \ (i = 1, \ldots, N-1)$ of multiplexed holograms

(2) Establish an objective function

$$E = E_1 + E_2$$

$$E_1 = \sum_{i=1}^{M}\left[\sum_{\substack{j=1\\ j\neq i}}^{N} W_{1ij}\left(\frac{P_{ij}}{\overline{P}} - 1\right)^2 + \sum_{j=2}^{N-1} W'_{1ij}\left(\frac{P'_{ij}}{\overline{P}} - 1\right)^2\right] \quad \text{for } P_{ij} \text{ and } P'_{ij} \geq \overline{P},$$

$$E_2 = \sum_{i=1}^{M}\left[\sum_{\substack{j=1\\ j\neq i}}^{N} W_{2ij}\left(\frac{\overline{P}}{P_{ij}} - 1\right)^2 + \sum_{j=2}^{N-1} W'_{2ij}\left(\frac{\overline{P}}{P'_{ij}} - 1\right)^2\right] \quad \text{for } P_{ij} \text{ and } P'_{ij} < \overline{P},$$

where $W^{(')}_{1ij}$ and $W^{(')}_{2ij}$ are weight factors

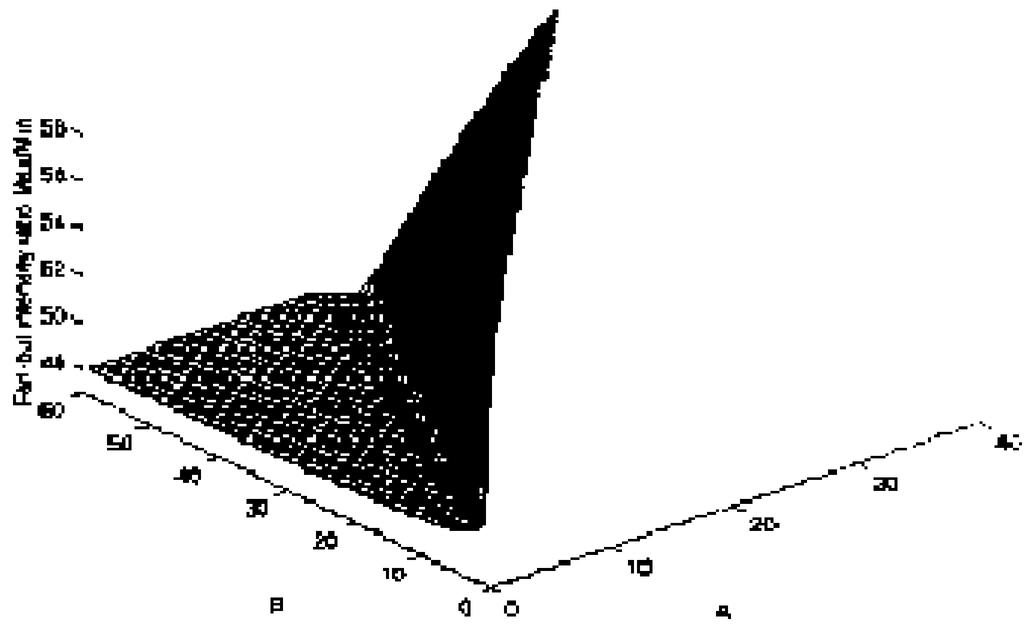
(3) Optimize the objective function through solving

$$\frac{\partial E}{\partial \eta_i} = 0, \quad i = 2, \ldots, N$$

Fan-out intensity optimization results (9-channel case)

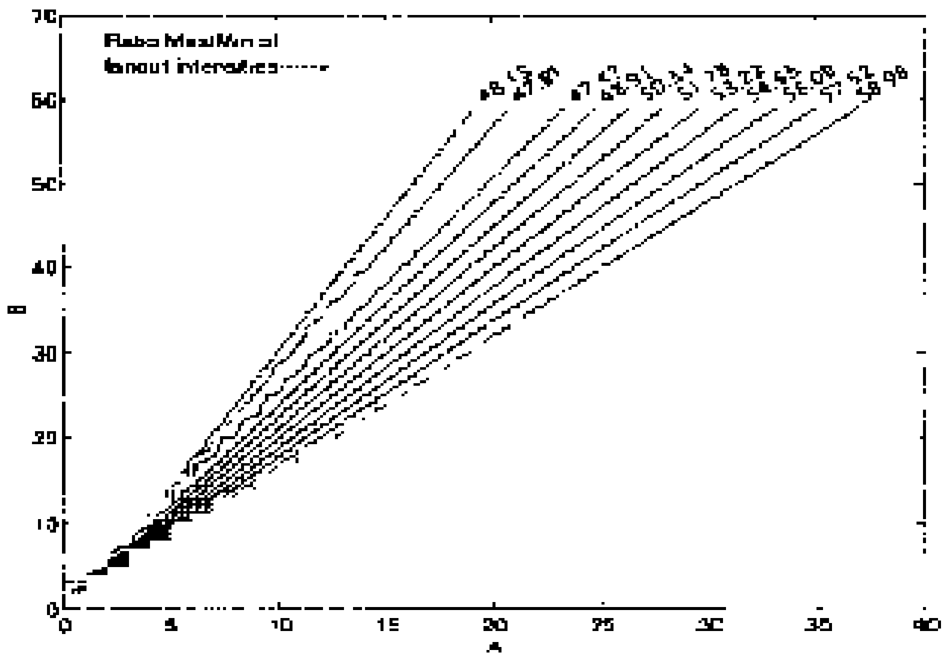
$$W_{1ij}^{(')} = \exp\left[A\left(\frac{P_{ij}}{\overline{P}} - 1\right)\right] \quad \text{for } P_{ij}^{(')} \geq \overline{P},$$

$$W_{2ij}^{(')} = \exp\left[B\left(\frac{\overline{P}}{P_{ij}} - 1\right)\right] \quad \text{for } P_{ij}^{(')} < \overline{P},$$



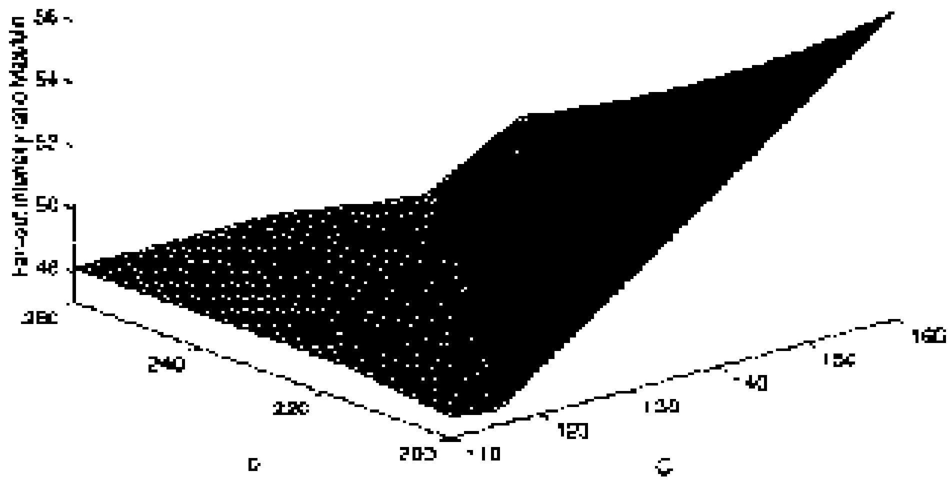
Fan-out intensity optimization results (9-channel case)

$$W_{1ij}^{(\prime)} = \exp\left[A\left(\frac{P_{ij}}{\overline{P}} - 1\right)\right] \quad \text{for } P_{ij}^{(\prime)} \geq \overline{P}, \qquad W_{2ij}^{(\prime)} = \exp\left[B\left(\frac{\overline{P}}{P_{ij}} - 1\right)\right] \quad \text{for } P_{ij}^{(\prime)} < \overline{P},$$



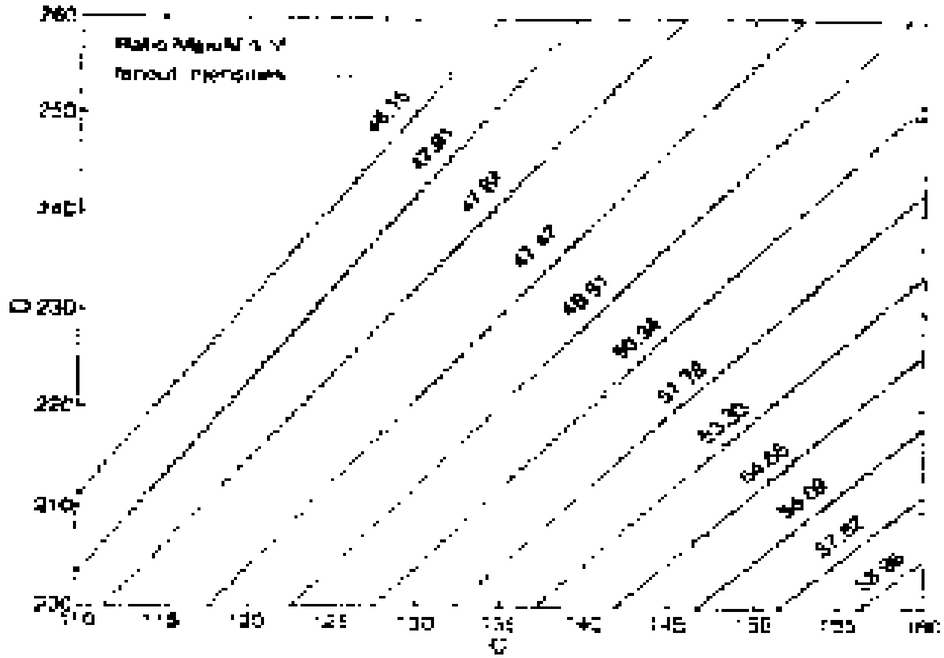
Fan-out intensity optimization results (9-channel case)

Different weight factors: $W_{1ij}^{(')} = \left(\frac{P_{ij}}{\overline{P}} - 1\right)^{C}$ for $P_{ij}^{(')} \geq \overline{P}$ $\quad W_{2ij}^{(')} = \left(\frac{\overline{P}}{P_{ij}} - 1\right)^{D}$ for $P_{ij}^{(')} < \overline{P}$



Fan-out intensity optimization results (9-channel case)

Different weight factors: $W^{(')}_{1ij} = \left(\frac{P_{ij}}{\overline{P}} - 1\right)^{C}$ for $P^{(')}_{ij} \geq \overline{P}$ $W^{(')}_{2ij} = \left(\frac{\overline{P}}{P_{ij}} - 1\right)^{D}$ for $P^{(')}_{ij} < \overline{P}$



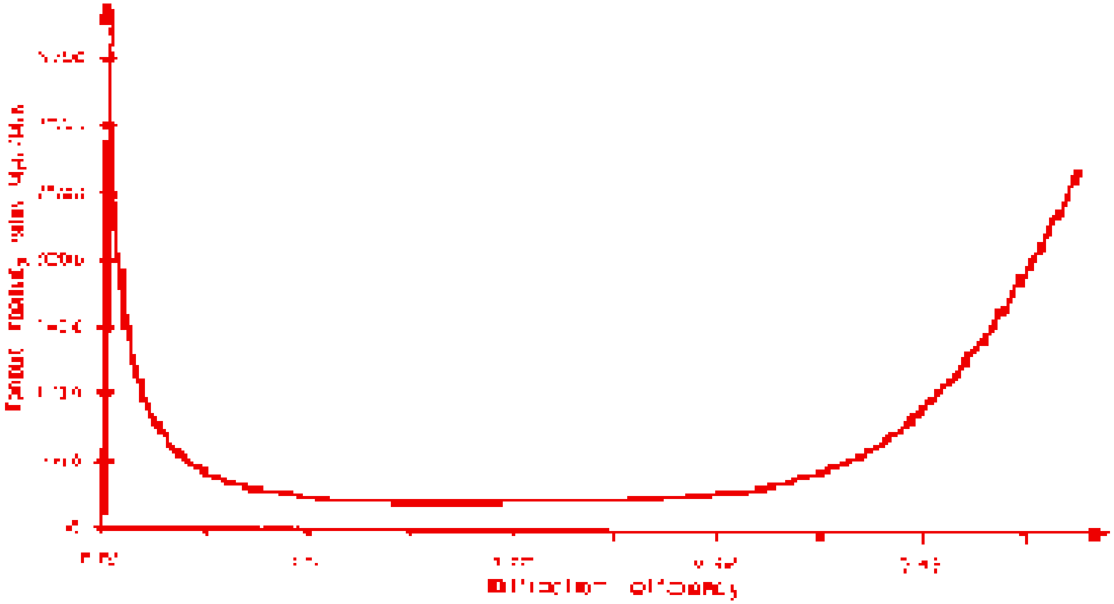
Optimized fan-out distribution

Optimized diffraction effiency distribution:

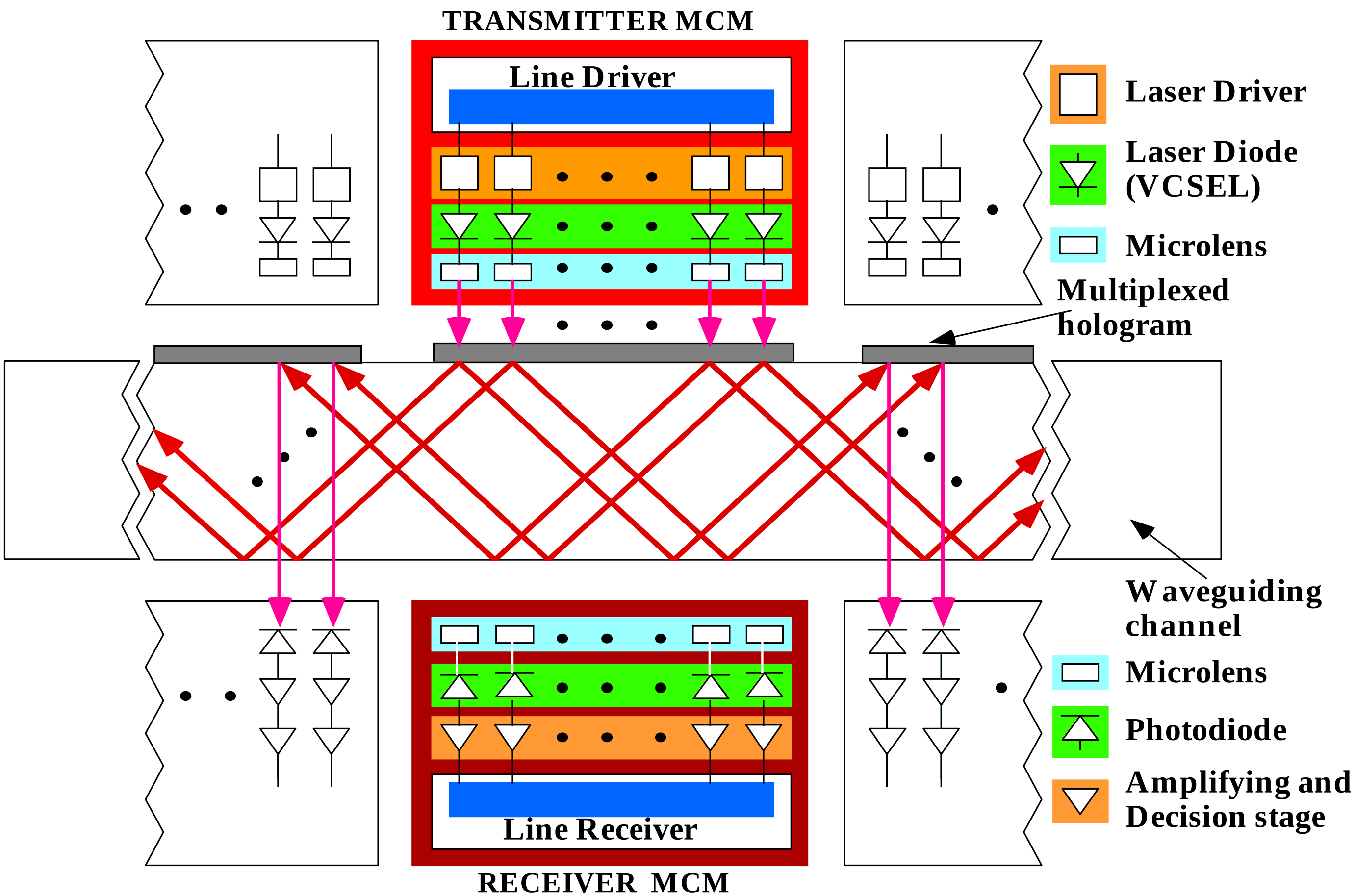
$(\eta_1, \eta_2, ..., \eta_9) = (1.0, 0.3341, 0.2005, 0.1435, 0.1548, 0.1665, 0.2492, 0.4984, 0.0)$

Fanout \ j	1	2	3	4	5	6	7	8	9
P_{1j}	0	0.27791	0.05833	0.02493	0.01860	0.01852	0.01698	0.01587	0.02131
P'_{1j}	0	0.16213	0.05758	0.02972	0.01653	0.01587	0.01587	0.01586	0
P_{2j}	0.44513	0	0.05853	0.02502	0.01867	0.01859	0.01703	0.01591	0.02138
P'_{2j}	0	0.17921	0.05777	0.02982	0.01659	0.01591	0.01591	0.01590	0
P_{3j}	0.07579	0.04219	0	0.02490	0.01858	0.01850	0.01696	0.01569	0.02129
P'_{3j}	0	0.04218	0.56723	0.02968	0.01651	0.01586	0.01586	0.01569	0
P_{4j}	0.02993	0.01666	0.02384	0	0.01858	0.01850	0.01696	0.01569	0.02128
P'_{4j}	0	0.01666	0.01667	0.70316	0.01651	0.01586	0.01586	0.01569	0
P_{5j}	0.02132	0.01587	0.01698	0.01853	0	0.01853	0.01698	0.01587	0.02132
P'_{5j}	0	0.01587	0.01588	0.01588	0.74511	0.01588	0.01588	0.01587	0

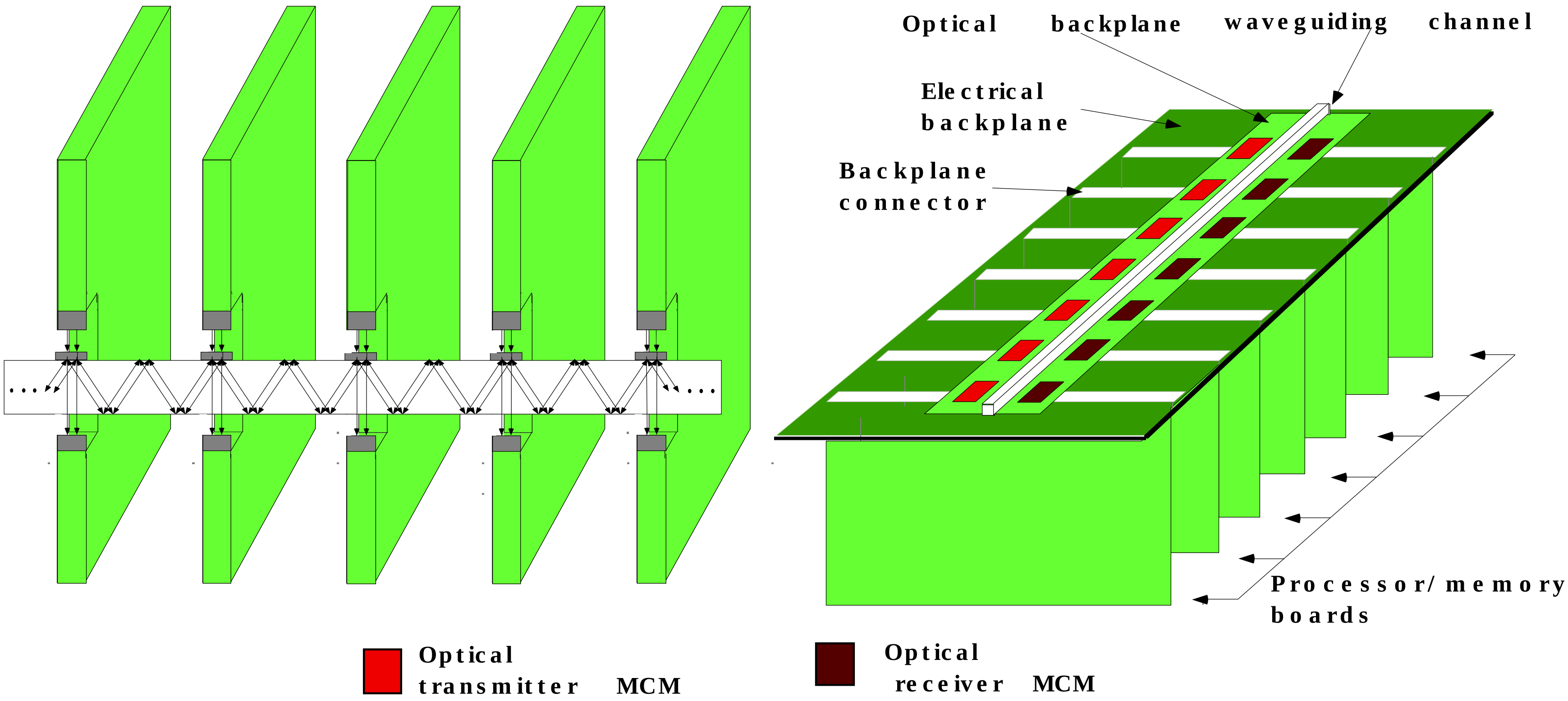
Fan-out intensity fluctuation of an unoptimized backplane



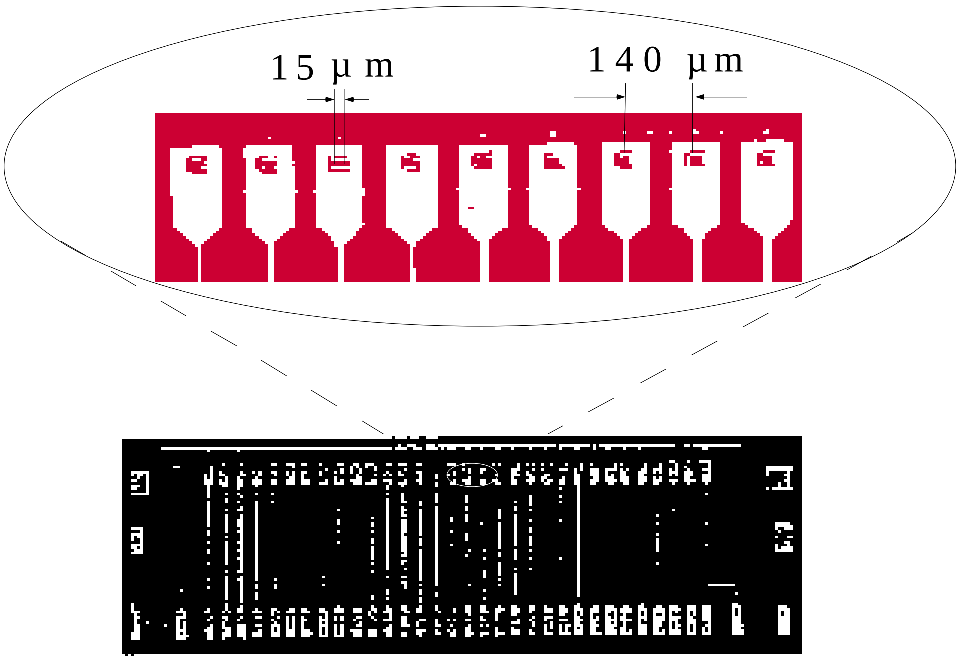
Bi-directional optical backplane bus with multi-bus lines: channel design



Bi-directional optical backplane bus with multi-bus lines: configuration



VCSEL array operating at 850 nm



Very low (1~3 mA or less) threshold current

High direct modulation bandwidth (over 14 GHz)

Moderate optical power (a few mW or more)

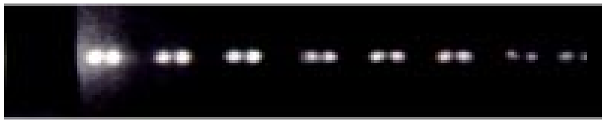
Wide operating temperature range (-55 to +125 ^{o}C)

Bi-directional optical backplane bus with multi-bus lines

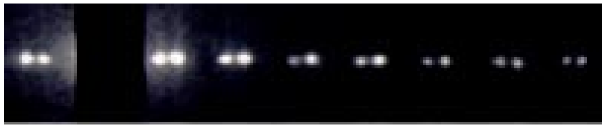
experiment demonstration

Input Channel:

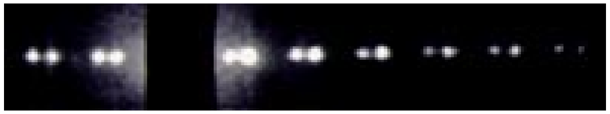
1st



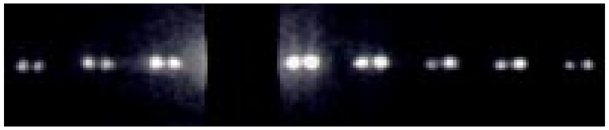
2nd



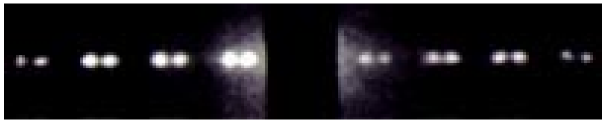
3rd



4th

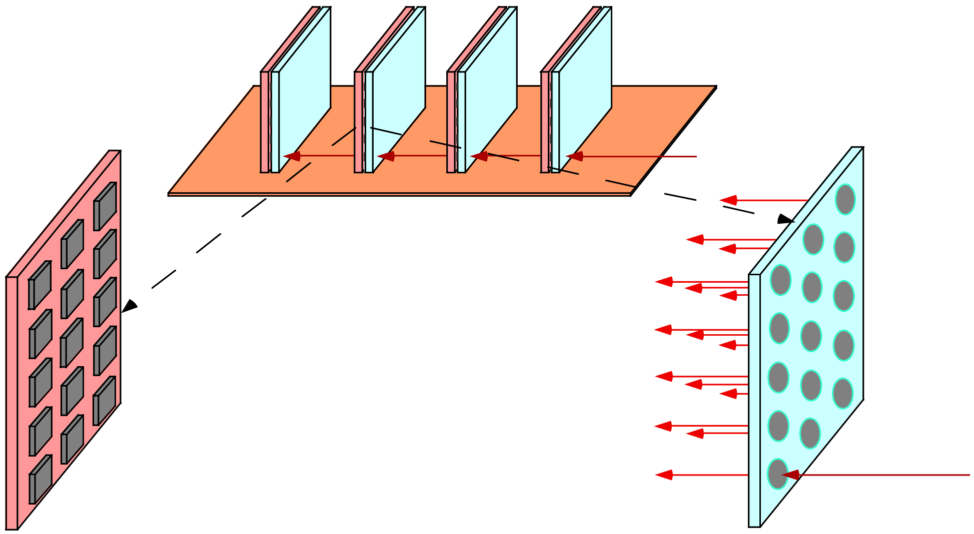


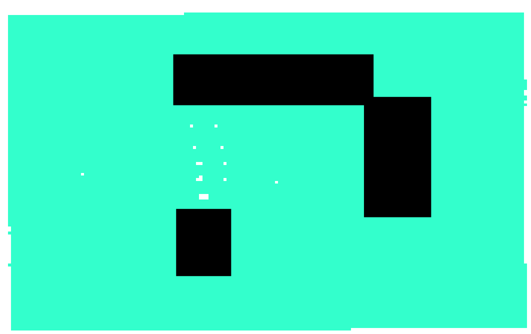
5th



Clock signal distribution system

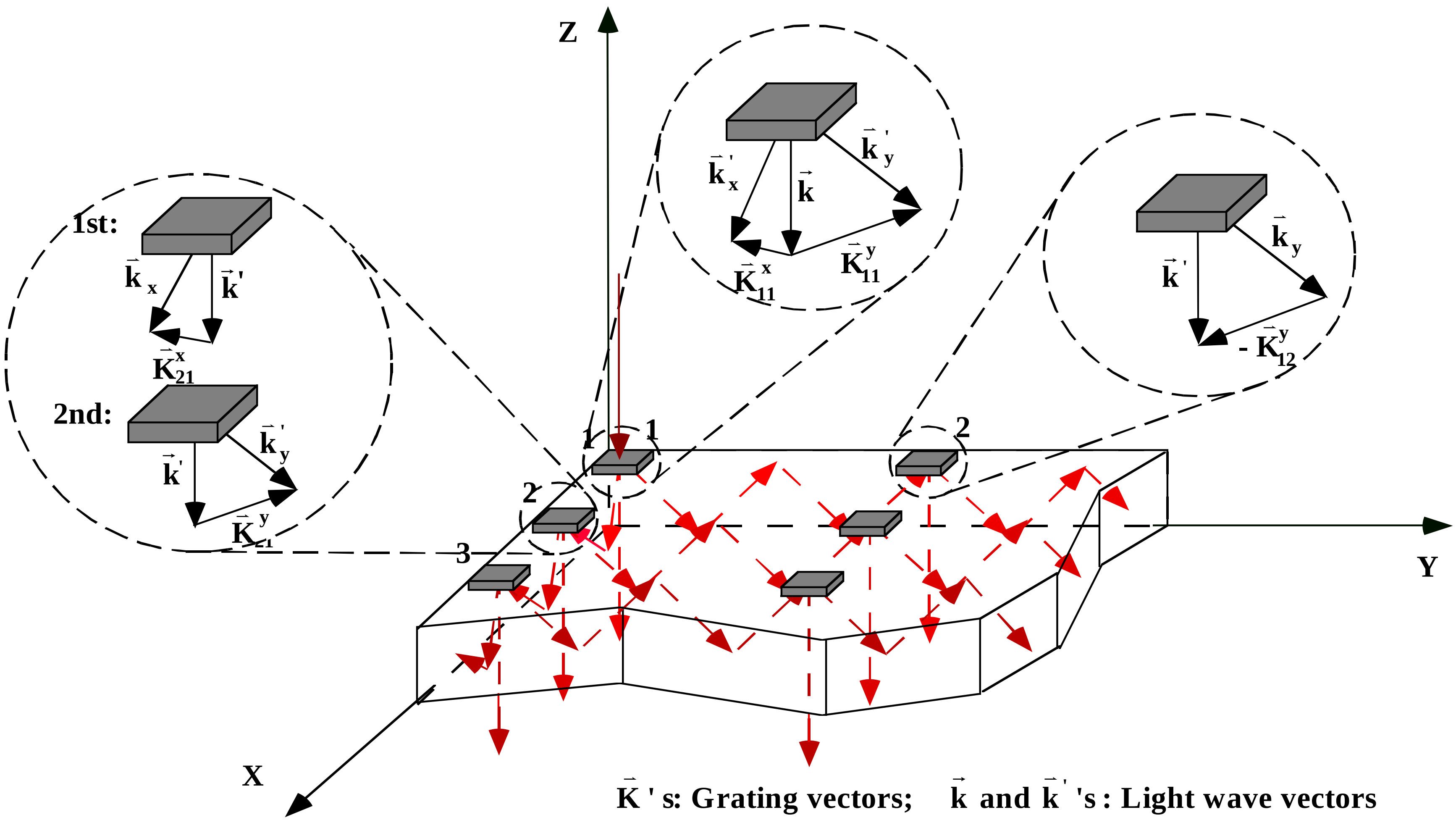
experiment demonstration





Clock signal distribution system

Device Analysis



$\vec{K}$'s: Grating vectors; $\vec{k}$ and $\vec{k}'$'s : Light wave vectors

Clock Signal distribution system

Fan-out intensity optimization (I)

Assume $M \times N$ fan-outs

Define:

Diffraction efficiencies:

$$\eta^x_i \; (i = 1, \ldots, M); \; \eta^y_{ij} \; (i = 1, \ldots, M; \; j = 1, \ldots, N)$$

Transmission functions:

$$T^x_i \; (i = 2, \ldots, M); \; T^y_{ij} \; (i = 1, \ldots, M; \; j = 2, \ldots, N)$$

Fan-out intensities: $P_{ij} \; (i = 1, \ldots, M; \; j = 1, \ldots, N)$

To minimize power consumption, we should have

$$\eta^x_M = 1; \; \eta^y_{iN} = 1 \; (i = 1, \ldots, M)$$

So the unknown η's are $(M - 1) + (M \times N - M) = M \times N - 1$

Clock Signal distribution system

Fan-out intensity optimization (II)

From Bragg diffraction analysis, we have (assume an input intensity of 1)

$$\begin{cases} T_2^x = \eta_1^x \\ T_i^x = T_{i-1}^x\left(1-\eta_{i-1}^x\right), \quad (i = 3, \ldots, M) \end{cases}$$

$$\begin{cases} T_{12}^y = \eta_{11}^y \\ T_{i2}^y = T_i^x \eta_i^x \eta_{i1}^y, \quad (i = 2, \ldots, M) \\ T_{ij}^y = T_{i,j-1}^y\left(1-\eta_{i,j-1}^y\right), \quad (i = 1, \ldots, M;\ j = 3, \ldots, N) \end{cases}$$

$$\begin{cases} P_{11} = 1 - \eta_1^x - \eta_{11}^y \\ P_{i1} = T_i^x \eta_i^x \left(1-\eta_{i1}^y\right), \quad (i = 2, \ldots, M) \\ P_{ij} = T_{ij}^y \eta_{ij}^y, \quad (i = 1, \ldots, M;\ j = 2, \ldots, N) \end{cases}$$

Clock Signal distribution system

Fan-out intensity optimization (III)

Define objective function:

$$\mathbf{E} = \mathbf{E}_1 + \mathbf{E}_2$$

$$\begin{cases} \mathbf{E}_1 = \displaystyle\sum_{i=1}^{M}\sum_{j=1}^{N}\left(\frac{\mathbf{P}_{ij}}{\overline{\mathbf{P}}} - 1\right)^2 & \text{for } \mathbf{P}_{ij} \geq \overline{\mathbf{P}},\ (i = 1, \ldots, M;\ j = 1, \ldots, N), \\ \mathbf{E}_2 = \displaystyle\sum_{i=1}^{M}\sum_{j=1}^{N}\left(\frac{\overline{\mathbf{P}}}{\mathbf{P}_{ij}} - 1\right)^2 & \text{for } \mathbf{P}_{ij} < \overline{\mathbf{P}},\ (i = 1, \ldots, M;\ j = 1, \ldots, N) \end{cases}$$

where $\overline{\mathbf{P}} = \dfrac{1}{\mathbf{M} \times \mathbf{N}}$ **is the average fan-out intensity**

<u>Optimization is carried out by minimizing objective function E</u>

Clock Signal distribution system

Optimized diffraction efficiency distribution (I)

For M = 6 and N = 7, $\bar{P} = 0.0238$, the optimized diffraction efficiency distribution for uniform fan-out intensity distribution is

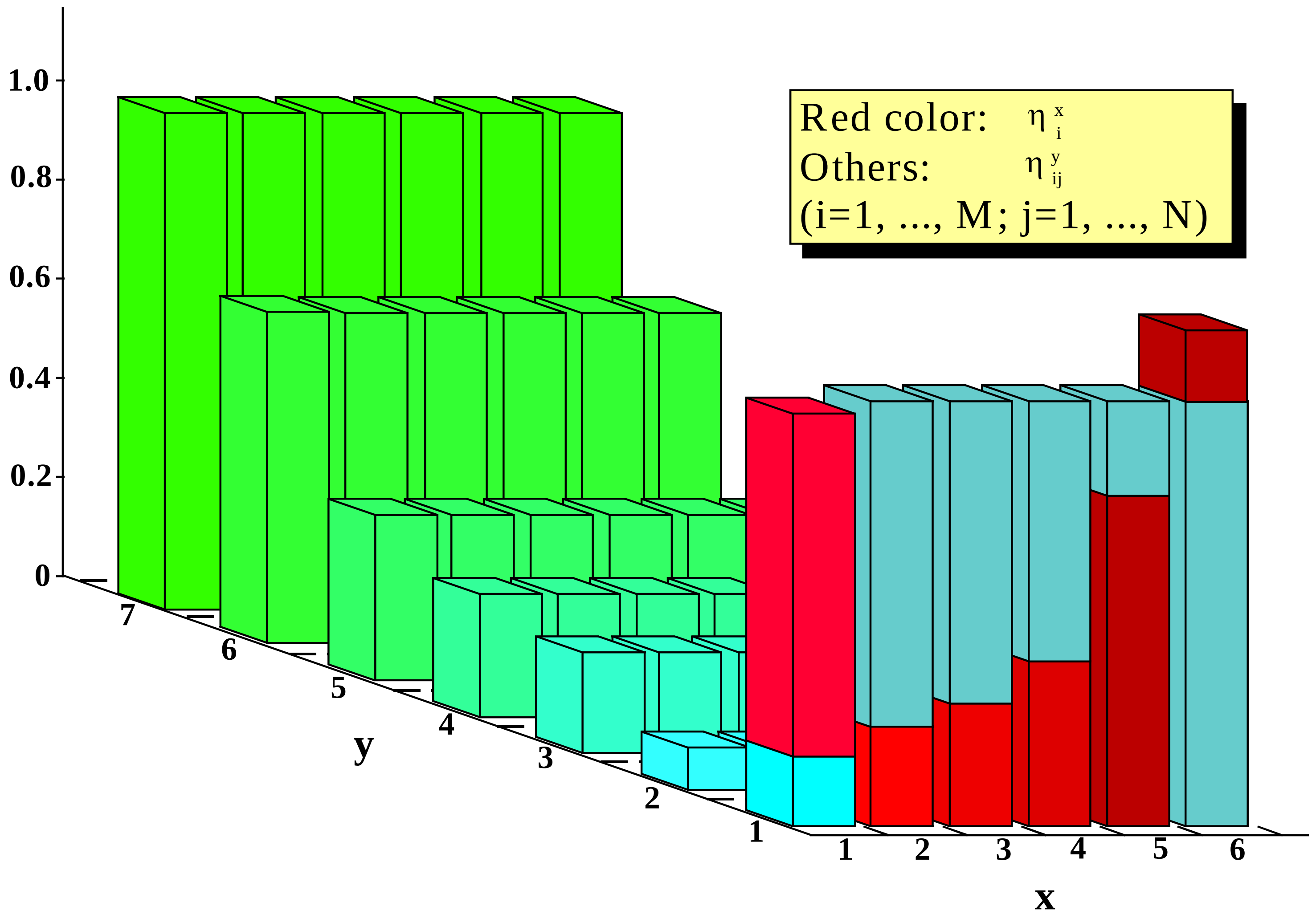
η^{y}_{ij} y / x	1		2	3	4	5	6	7
	η^{x}_{i}	η^{y}_{i1}						
1	0.833	0.143	0.167	0.200	0.250	0.333	0.500	1.000
2	0.200	0.857	0.167	0.200	0.250	0.333	0.500	1.000
3	0.250	0.857	0.167	0.200	0.250	0.333	0.500	1.000
4	0.333	0.857	0.167	0.200	0.250	0.333	0.500	1.000
5	0.500	0.857	0.167	0.200	0.250	0.333	0.500	1.000
6	1.000	0.857	0.167	0.200	0.250	0.333	0.500	1.000

Clock Signal distribution system

Output fluctuation without optimization

Clock Signal distribution system

Optimized diffraction efficiency distribution (II)



Clock Signal distribution system

Clock skew and time jittering analyses

- **Time delay**: **(deterministic) difference in clock paths**

  For our device with 6 $\times$7 fan-outs , waveguide thickness of 1 mm and bounding angle of 45^{o}

  Maximum time delay=150 ps

- **Clock skew** : **(non-deterministic) clock-to-clock variation of clock edges**

  * **spatial skew:**

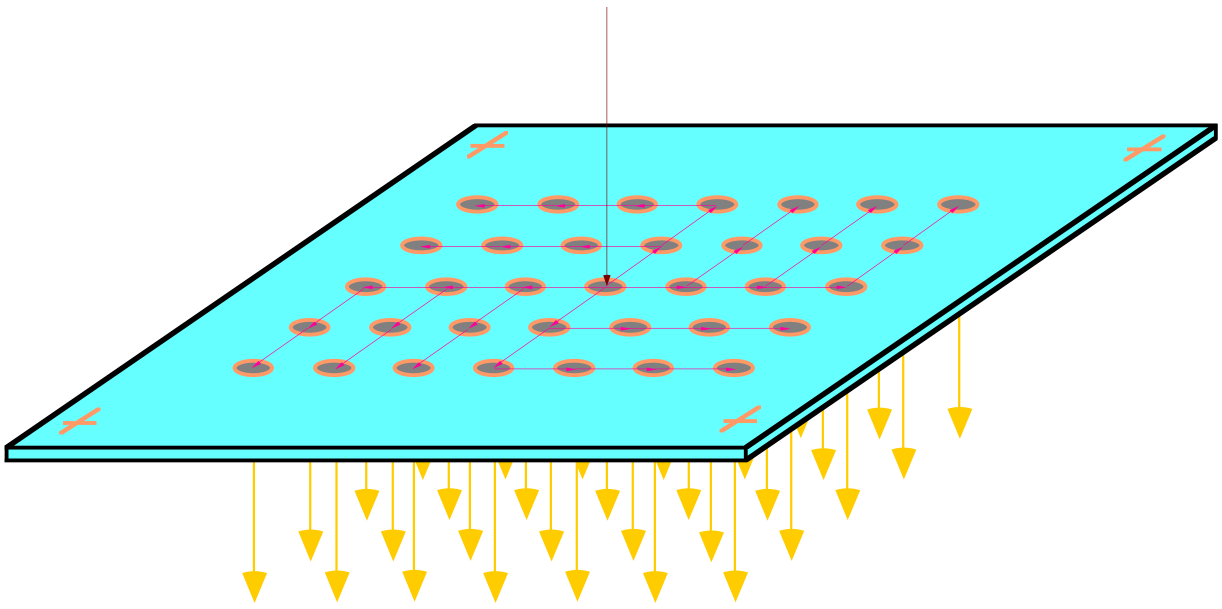
    variation in fabrication process

  * **temporal skew:**

    noise from clock laser, clock device, receiver, etc

Clock Signal distribution system

Reduction of time delay



Optical backplane and clock Signal distribution systems

Power budget considerations

APD: At 850 nm, 500 Mbit/s, BER=10^{-9}

dynamic range 30 dB, sensitivity = -45 dBm

Optical clock signal distribution system:

$$P_{out} = \frac{(1-R)P_{in}}{M \times N}$$

=> required VCSEL power range 1.89 µW-1.89 mW

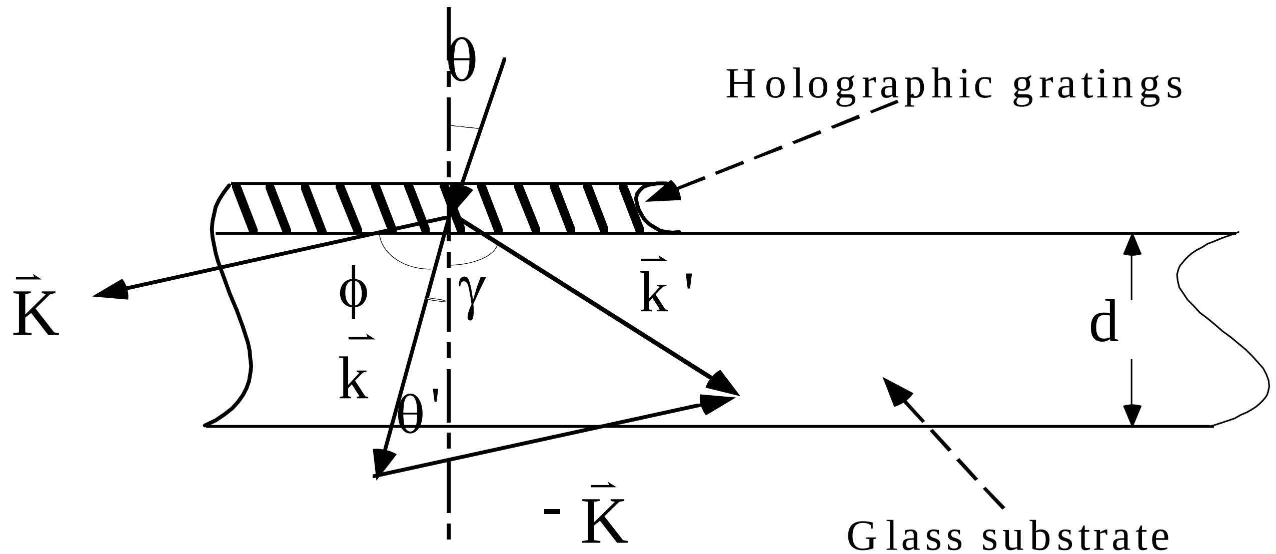
Optical backplane system:

$$P_{out} = \eta(1-R)P_{in}$$

=>required VCSEL power range 3.0 µW-3.0 mW

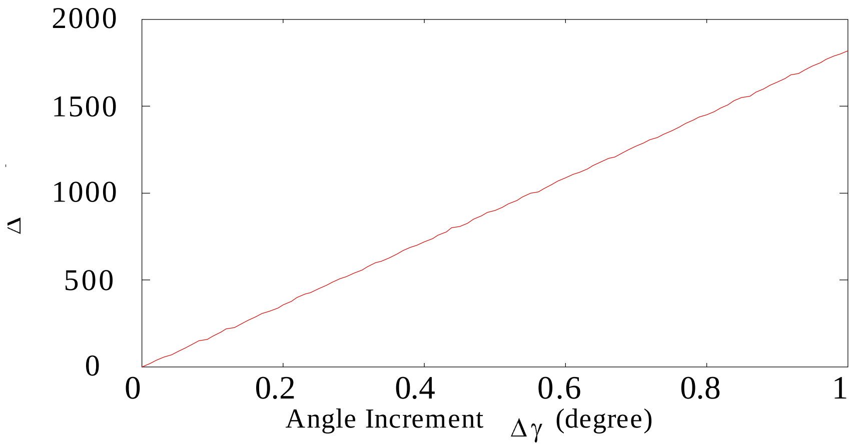
Optical backplane and clock Signal distribution systems

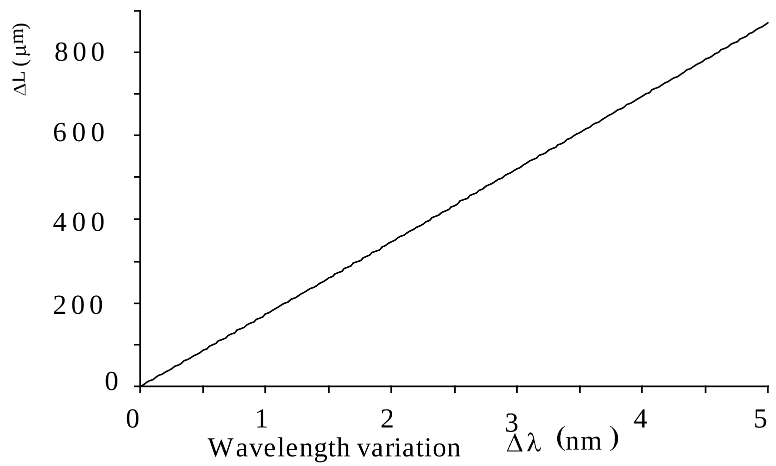
Misalignment consideration(I)



Optical backplane and clock Signal distribution systems

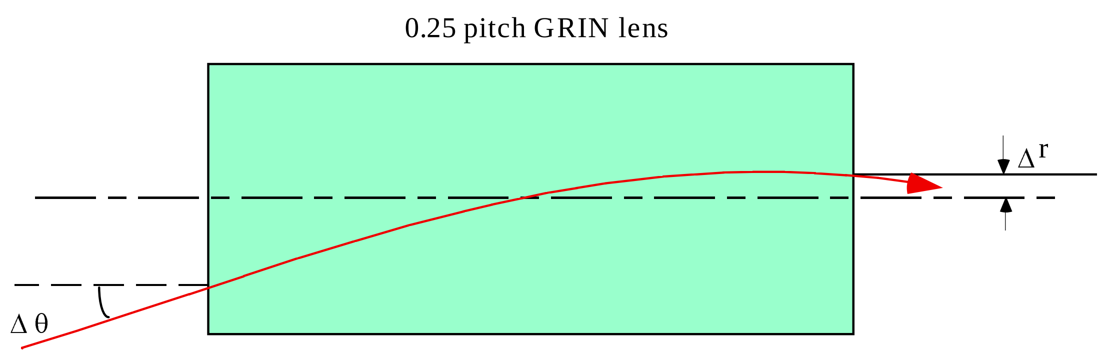
Misalignment consideration(II)





Optical backplane and clock Signal distribution systems

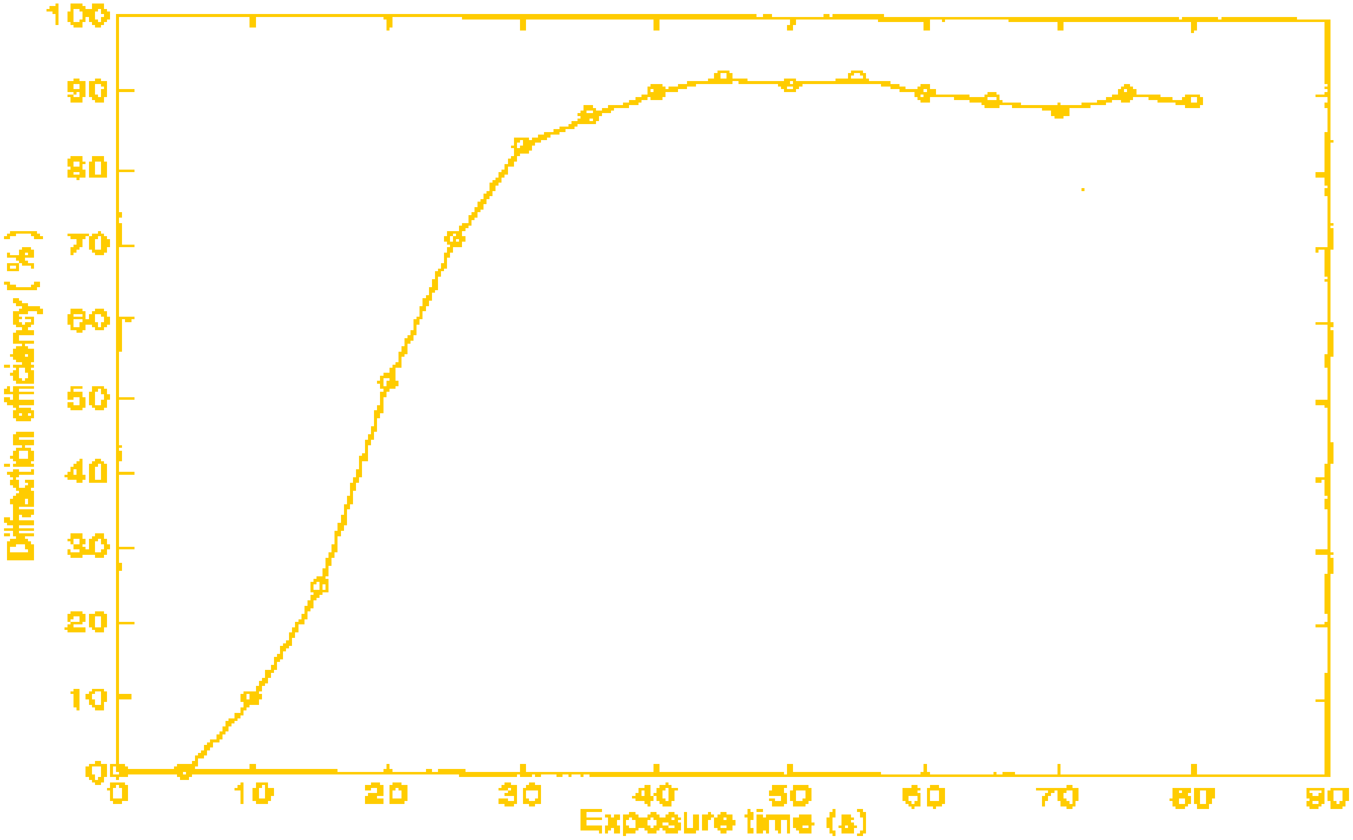
Beam collimation



For 2 ^{o} input angle, spatial shift out of GRIN lens 50 μm

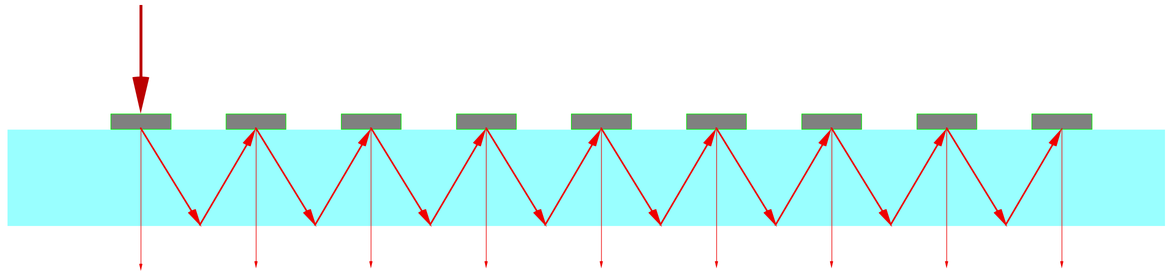
Study of Dupont photopolymer film

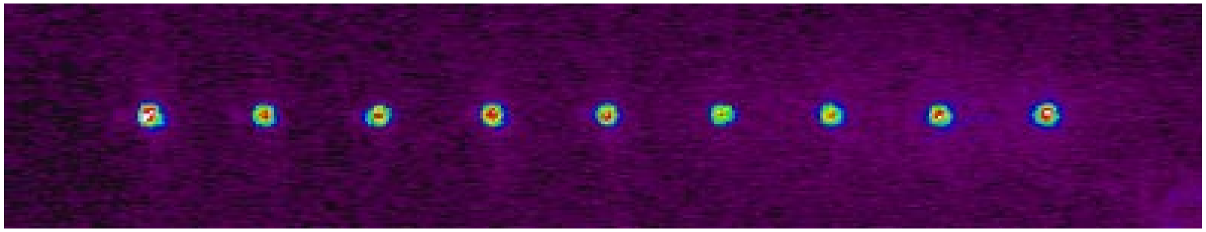
Diffraction efficiency



Study of Dupont photopolymer film

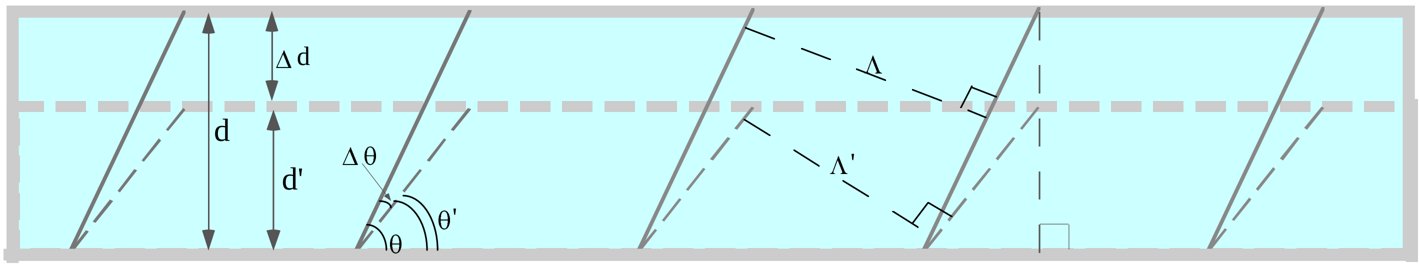
1-to-9 equal fan-out device demonstration





Study of Dupont photopolymer film

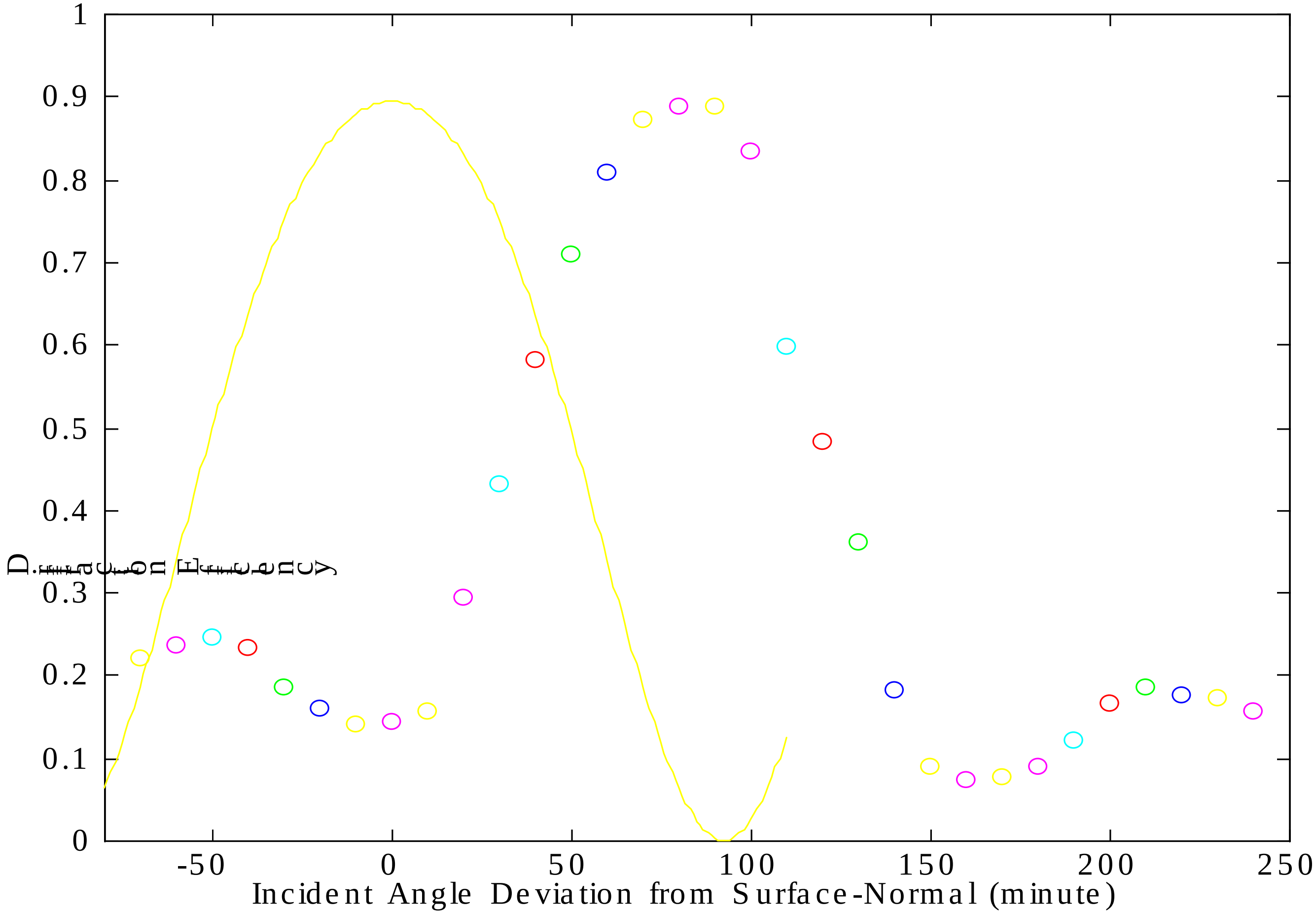
Thickness variation phenomenon



Refractive index: $n(\vec{r}) = n_0 + \Delta n(\vec{r})$

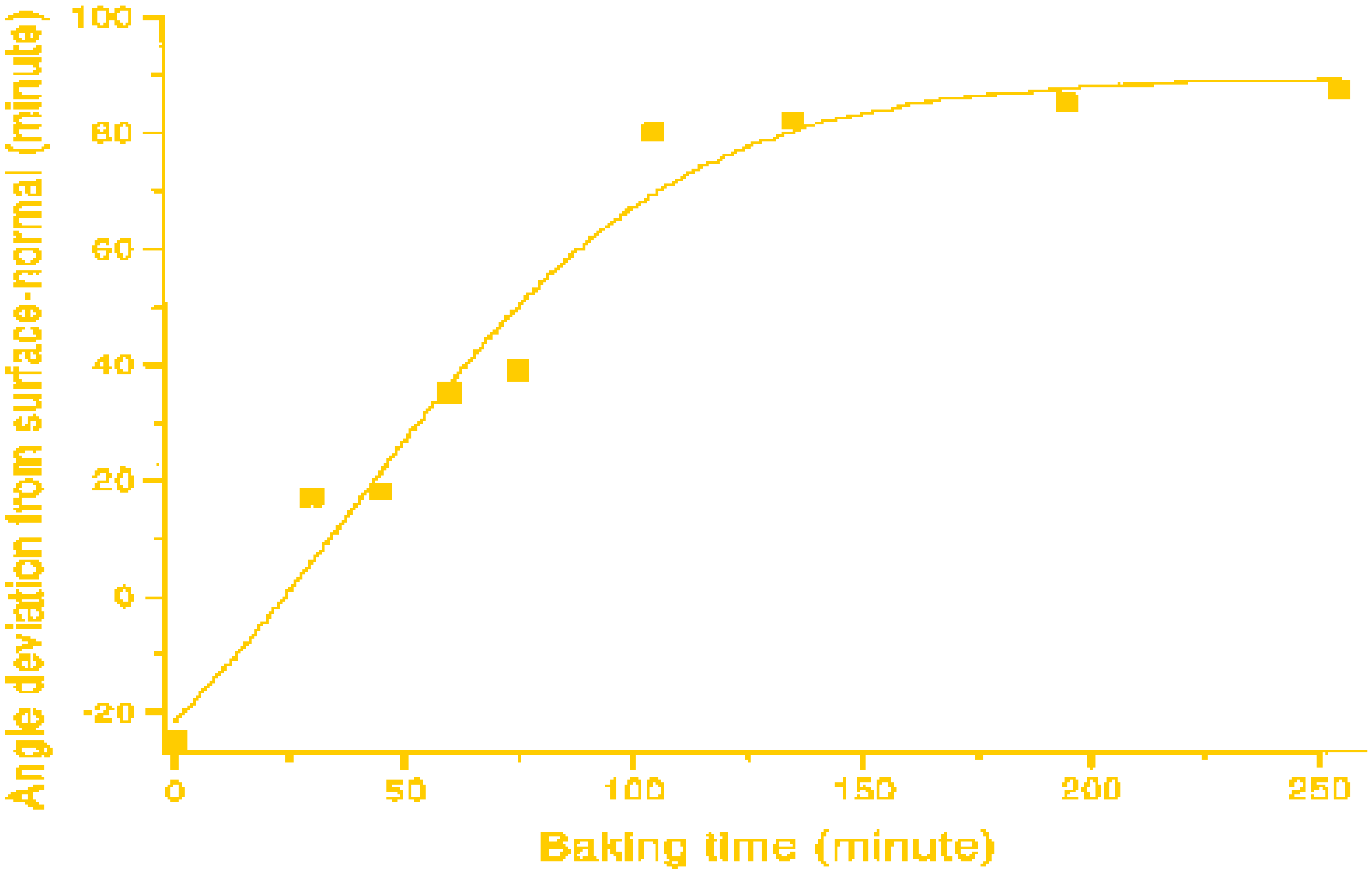
Study of Dupont photopolymer film

Comparison of theoretical and experimental efficiency curves



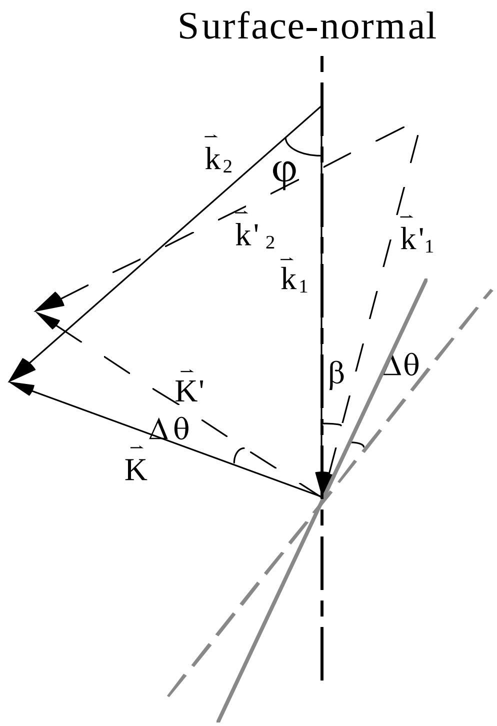
Study of Dupont photopolymer film

Variation of Bragg angle with baking time



Study of Dupont photopolymer film

Theoretical study of thickness variation

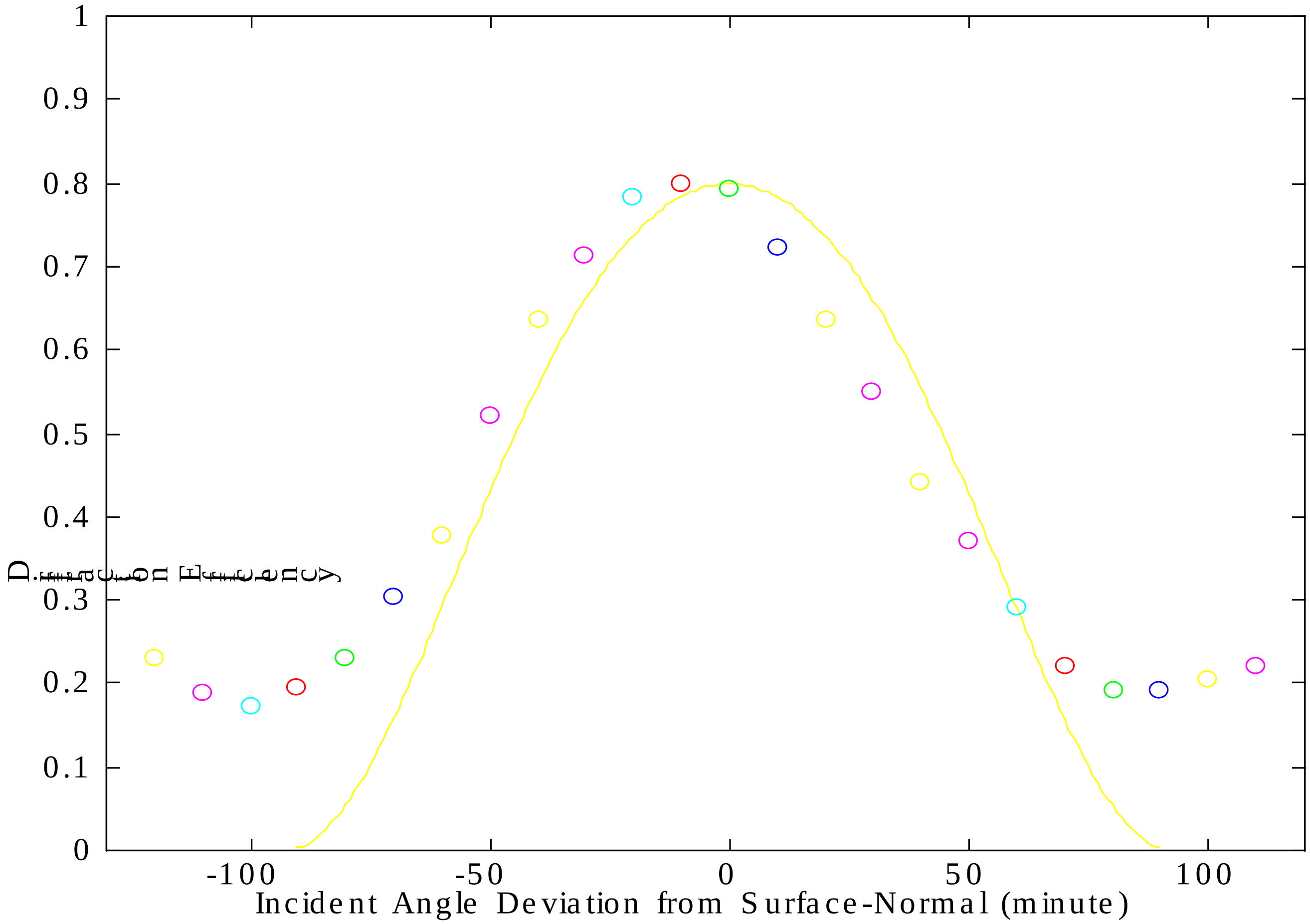


For 20 μm film, deviation angle of 85',

get $\Delta d = 1.05\ \mu m$ or $\Delta d\% = 5.25\%$

Study of Dupont photopolymer film

Compensated results

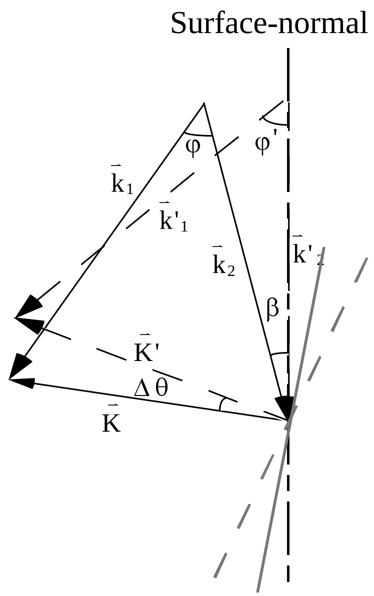


Study of Dupont photopolymer film

Compensation for thickness variation

Assumption :

For two holograms fabricated under the same recording beam intensity and recording time, and the same condition for other processes, the resulted relative changes in film thickness wilbe the same



Proposed future works

Fabrication of power-budget-optimized devices

(1) Use the results from the experiment of Dupont photopolymer efficiency measurement

Tune the efficiencies of the holographic gratings according to optimization results

(2) Use the compensation method to adjust the Bragg condition to be surface-normal

Proposed future works

Time jittering measurement of the clock distribution device

(1) Directly modulate a VCSEL with a digital signal synthesizer

(2) Measure the output signals with and without the device

(3) By comparing the transition times for the signal edges crossing the threshold level, can get the jittering due to the device

Proposed future works

Eye diagram measurement of the devices

(1) Modulate the VCSEL with a randomized bit generator with a periodic $(2^{31}-1)$ pseudorandom bit sequence

(2) Measure the output signals from the detector with and without the devices

(3) Compare the eye patterns to check the performance of the devices

Proposed future works

Crosstalk measurement of the backplane device

(1) Couple the output from a VCSEL into the device using lenses with different radius

(2) Measure the output signal profiles from the device (Central intensity and FWHM)

(3) Calculate the crosstalks by assuming a Gaussian distribution of the profiles

Proposed future works

Finally, integrate the VCSEL arrays and detectors

(arrays, if we can get some)

for system demonstration